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MULTISENSORY INTEGRATION FOR PILOT SPATIAL ORIENTATION (MIPSO)

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Final Report for the Period June 2003 to March 2004

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FOR THE COMMANDER

//Signed//

MARIS M. VIKMANIS
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13. ABSTRACT *(Maximum 200 words)*

Spatial disorientation (SD) is a normal human response to accelerations in flight, and has existed since early flight. Its cost to the US military is over $300 million per year, with comparable costs to US civil aviation. Despite significantly increased research over the past decade, the rate of accidents caused by SD has not decreased. While the most recent research emphases have been on understanding the physiology of SD, the translation of the new knowledge into tools (e.g., training, displays, automation) that help pilots avoid SD and minimize its effects if it does occur, has not occurred. The goals of the research reported here were to apply multisensory countermeasures to SD based on human sensory models and the pilot's workload. It is the premise of this Phase I effort that more effective multisensory countermeasures, applied in an intelligent fashion, are needed and possible, and that modeling and simulation are the most cost effective means to identify and test countermeasures for different aircraft under varying conditions.

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Executive Summary

Spatial disorientation (SD) is a normal human response to accelerations in flight (Previc, 1998), and has existed since early flight (Ocker & Crane, 1932; Macurdy, 1934). Its cost to the US military is over $300 million per year (Heinle, 2001; Davenport, 2000), with comparable costs to US civil aviation (Veronneau, 2000). Despite significantly increased research over the past decade (Previc & Ercoline, 2001), the rate of accidents caused by SD has not decreased (Ercoline et al., 1994a). While the most recent research emphases have been on understanding the physiology of SD, the translation of the new knowledge into tools (e.g., training, displays, automation) that help pilots avoid SD and minimize its effects if it does occur, has not occurred.

The goals of the research reported here were to apply the recent research results to practical methods that enhance pilot attitude awareness and combat SD. The vast majority of SD-induced accidents are from Type 1 (unrecognized) SD (Ercoline & Previc, 2001). The major challenge, then, is to convert Type 1 SD events into Type 2 (recognized) events so that the pilot can recover. A solution, even a partial one, to Type 1 SD events will greatly improve the appalling SD accident statistics.

Considerable progress has been made in providing pilots with countermeasures to SD. It is the premise of this Phase I effort that more effective multisensory countermeasures, applied in an intelligent fashion, are needed and possible, and that modeling and simulation are the most cost effective means to identify and test countermeasures for different aircraft under different flight conditions.

There are 8 chapters in this report. The first chapter describes the impact and nature of spatial disorientation in aviation. The 2nd chapter gives a brief background on the neuro-physiological processes that underlie SD. The 3rd chapter describes multisensory cockpit technologies that could reduce the quantity and severity of SD mishaps. The 4th chapter presents our innovative theoretical and practical approaches to modeling pilot attitude awareness and SD. Our approach demonstrates how human performance modeling can be used to study the effects of SD reduction from new and future cockpit technologies, and thus to reduce the time and costs needed to test prototypes and to push more promising technologies into flight test sooner than with a more traditional approach. Modeling also suggests effective training strategies and scenarios.

Realistic Air Force scenarios are in Chapter V. These mission scenarios put the pilot at considerable risk of disorientation and serve as the foundation for our SD Aiding System prototype's testing and demonstration. The scenarios include a slow-onset Leans event, which is the most common SD event, as well as a quick-onset Coriolis event, which is one of the most compelling and lethal types of disorientation. Our assertion is that if we can credibly model these types of disorientation events and aid in their recovery, our approach will be extendable to other SD illusions. (And, in fact, when we received actual flight data from the Air Force Safety Center, that data set ran reasonably well through our SD Aiding System, proving its robustness.)

The 6th chapter provides the rationale and design for an intelligent aiding system that helps with SD event recoveries. The 7th chapter highlights our major accomplishments in Phase I. Chapter VIII discusses Phase II goals and plans. The emphases in Phase II will be to validate our models via human-in-the-loop testing, and then to evaluate our model-based countermeasures via pilot-in-the-loop experiments.

I. Introduction

Spatial disorientation (SD[1]), simply referred to as vertigo until becoming the subject of scientific research, is a normal response to neuro-physiologically confusing stimuli in the flight environment. The human body developed over eons to perceive motion on land in relation to the surface of the earth. In flight, these physiological systems can give the brain erroneous orientation information. Everyone who flies will eventually experience some of these phenomena; some pilots will experience them more acutely than others.

An increased reliance on air power, the current USAF advantage in night operations, and the emphasis on reduced crew numbers will accelerate the already increasing incidence of tragedies that result from difficulties of the human sensory system to spatially orient in the 3D world of flight. In order to advance our mastery of the flight environment, a thorough understanding of disorientation phenomena and appropriate countermeasures must be devised. The focus of this report will be to recommend a modeling and simulation approach that will be based in human neuro-physiology, flight dynamics, and physics, which will enable the rapid and economical prototyping of disorientation countermeasures.

This conflict between one's senses and reality has received much recent research attention.[2] Understanding the physiological causes of SD is essential to solving the problem, and will be discussed in Chapter II of this report. A next step is to quantify the contributory values or ranges for the various physiological mechanisms. For example, how much do optical illusions contribute to SD-related accidents? How effective is a particular attitude display in helping to maintain SO? Some answers are beginning to emerge. For example, Gomez (2002) asserts, "90% of all inputs to the brain that give the sense of orientation are visually acquired." This assertion implies that SO displays should be visual, as opposed to auditory or tactile displays, which, presumably, contribute only 10% of the orientation inputs to the brain. However, the SD problem is too important to rely on only one sensory channel. Also, because SD is often due to a sensory conflict or distraction, using only one sense (vision) to combat it is ill advised. A multisensory approach is needed.

Terminology

Several definitions have been proposed for SD to help guide research and a generally accepted working definition has emerged (Ercoline et al., 1994b). A pioneer in the field of SD provided the following operational definition of SD as "an erroneous sense of the magnitude or direction of any of the aircraft control and performance flight parameters" (Gillingham, 1992).

For the purposes of this report, we consider SD in layman's terms as a loss of attitude awareness, and not as a loss of geographical awareness. Attitude awareness is the pilot's active knowledge of the aircraft's pitch, roll and yaw (particularly the first two), and the likely near-future values of those factors that comprise aircraft attitude. We place attitude awareness (and spatial disorientation) in the broader context of situation awareness and spatial orientation as follows:

[1] All acronyms are defined in the last chapter of this report.

[2] For example, the Spatial Disorientation Symposium (Nov 2000) in San Antonio, TX had the following relevant presentations: Gallimore, J.J. & Liggett, K.K. *Implications of spatial sensory reflex research on primary flight display design* and Cheung, R. *Non-visual spatial orientation mechanisms*. See also the web site: http://www.spatiald.wpafb.af.mil/library_san.asp.

Situation awareness, the broadest concept, defines the pilot's understanding of the current and future situation pertaining to any of a number of dynamic variables in the cockpit, such as the status of automation, task completion, or the spatial behavior of the aircraft. The latter form of situation awareness defines **spatial awareness** or **spatial orientation**. Spatial orientation in turn, pertains to knowledge of three types:

i. Where am I (location, altitude)?
ii. Which way am I going (velocity vector: trajectory and vertical velocity)?
The answers to questions (i) and (ii) define **geographical awareness**.
iii. Which way is up (pitch and bank)?
The answer to question (iii) therefore defines **attitude awareness**.

Thus spatial disorientation refers to the loss of attitude awareness. As we will see, this loss is caused by degraded visual information regarding the true horizon, plus the input of misleading vestibular signals.

There are presently three types of SD, as identified by researchers (Ercoline & Previc, 2001):

- Type 1, **unrecognized**, SD: Refers to the conditions that occur when a pilot is not aware of critical control or flight parameters of the aircraft. The aircraft is controlled, therefore, with erroneous assumptions of the aircraft attitude. Type I SD is generally considered to be the most deadly since the pilot is not aware that anything is wrong (Brown et al., 2000). It is the most common type, usually associated with sub-threshold roll or pitch motion, and it may be due to distraction or target fixation, such that the pilot does not pay sufficient attention to the aircraft attitude. Especially in civil aviation, SD results from relatively inexperienced pilots flying into poor or marginal weather, losing their normal visual attitude cues, having a trigger event (e.g., a distraction or moving the head off-axis, such as to look for and pick-up a chart), and "letting" the aircraft slip into an undesirable attitude (Veronneau, 2000).

- Type 2, **recognized**, SD: Associated with known conflicts between 2 or more orientation senses, such as degraded vision and otolith stimulation. Type 2 SD includes those mis-haps in which there is a conscious conflict between what the pilot is sensing and what the instruments indicate the airplane is doing. In this type of SD, pilots typically believe that the aircraft instruments are malfunctioning; they may not believe that they are disori-ented, but they know that something is wrong. Training typically focuses on what to do: believe the instruments, fly a smooth recovery, and exit the conditions that led to SD as soon as possible.

- Type 3, **incapacitating**, SD: Typically, the pilot is aware of losing SO, is trying to correct the problem, but is unable to provide the necessary aircraft inputs. There are often fatal results due to a complete loss of aircraft control.

Some disorienting illusions fit nicely and uniquely into the type categories whereas some transi-tion from one type to another, such as when a pilot initially does not recognize an SD event, but then does detect it. Early pilots discovered all of the illusions that we know about today; only the names and physiological explanations have changed. Unfortunately, the frequency of inci-dents has increased as more physiological demands are placed on the pilots of high performance aircraft.

Spatial disorientation and loss of geographical awareness are distinct, and lead to different classes of accidents. Loss of geographical orientation is a major cause of controlled flight into terrain (CFIT) accidents. Here the aircraft is clearly under effective pilot control. In contrast, SD (loss of attitude awareness) involves an explicitly uncontrolled aircraft, leading to the class of SD accidents.

While loss of geographical awareness and spatial disorientation (SD) are thereby distinct due to their association with geographical awareness and attitude awareness, respectively, the two states are nevertheless closely linked. First, any unnoticed bank or pitch (Type 1 SD) will typically lead to a loss of altitude, and therefore to trajectories toward the terrain. Second, any noticed attitude changes (Type 2 SD) can easily lead to a diversion of attention away from navigation and maintaining geographical awareness, as the pilot places top priority on recovering attitude.

When phrases such as loss of situational awareness (LSA) and CFIT are used in the aerospace literature concerning experimental research and accident investigation, care should be taken to use them in ways that will clarify the issues and avoid confusion with SD. Unfortunately, the research areas for LSA and CFIT are not as mature as the SD research. It is also clear that SD researchers do not often consider the wealth of ideas in the LSA literature; nor do the SA investigators seem to be acquainted with the SD literature as well as might be expected. As Lawson et al. (2002) point out, the two distinct fields of research could benefit from a better acquaintance as they have much in common.

Magnitude of the Problem

The seriousness of SD phenomena to the flight environment cannot be overstated. Of 323 of the most serious (Class A[3]) mishaps in the U.S. Air Force from 1991-2000, 20.2% were SD related (Davenport, 2000). Further, it is estimated that 89% of general aviation SD events are fatal (Nall, 1999). Survivors are typically non-instrument rated pilots suddenly in awful meteorological conditions trying to complete their flights and often are fortunate just to survive. Holmes et al. (2003) have estimated that roughly 80% of pilots have directly experienced SD incidents, although these typically do not lead to mishaps. SD mishaps are often fatal, accounting for the loss of about 40 lives per year in the U.S. Air Force, Navy and Army combined (Braithwaite et al., 1998; McGrath, 2000).

Estimates vary widely concerning the prevalence of SD-related mishaps (Lyons et al., 1994). Gillingham (1992), Lyons et al. (1994) and Johnson (2000) believed that most published SD estimates were too conservative. Gillingham (1992) pointed out problems with mishap classification and conjectured that SD caused as many as 2-3 times more U.S. Air Force mishaps than the reported statistics indicate. Johnson (2000) stated that SD mishaps in the U.S. Navy may be twice as likely as the statistics portray, accounting for 26% of all Class A mishaps (US Navy, 1991), and claiming nearly three times more lives than non-SD mishaps.

Lyons et al. (1994) discussed several classification problems they observed in USAF mishap data, including failure to clarify the relationship of SD to mishaps that involved continuing visual flight into adverse weather. Lyons et al. (1994) noted that a simple change in the accident reporting form increased the rate of categorization of accidents as SD-related. Whereas the old

[3] Class A mishaps result in loss of life, or at least a million dollars in damage, or the destruction of an aircraft.

accident investigation form listed "visual illusions" and "disorientation/vertigo" as choices, the new form substituted the currently accepted types of SD as possible choices on the form. When the three types of SD were listed on the form, the result of this change was an increase in choosing SD as a causal factor during low-level navigation, from 7% with the old form (FY86-FY89) to 67% with the new form (FY90-91). One of the key advantages of the newer form was that it listed "unrecognized SD" (Type 1). This change implicitly promoted the selection of SD as a mishap contributor in cases where the pilot did not report having suffered an acute and recognizable vestibular illusion, such as an attack of *the Leans*, but the accelerations the pilot experienced and the control inputs the pilot made indicated that the pilot was spatially disoriented (Benson, 1988).

Gillingham (1992) summarized 633 of the Class A aircraft mishaps in the U.S. Air Force from 1980-1989 (Table 1). During this period, 356 mishaps were "operations related," 81 mishaps were classified as "SD-related" and 263 as "LSA-related." However, there were 270 mishaps where SD and LSA were both mentioned as contributing factors.

Table 1. 1980-1989 USAF Class A aircraft mishaps – as categorized by Safety Investigation Boards (Gillingham, 1992).

	Total	% Operations Related	**% SD Related**
Mishaps	633	56%	**13%**
Costs	$4.45B	$2.56B	**$539M**
Fatalities	795	65%	**15%**

Cheung and colleagues analyzed SD-related accidents in the Canadian forces (Cheung et al., 1995). They collected 154 accident reports across Categories[4] A, B, and C. They found that 14/62 (23%) of Category A accidents had SD as a possible causal factor during the period 1982-1992; SD was unrecognized by the aviator in all but two of the 14 accidents, and two of the accidents appeared to be of vestibular origin.

Davenport (2000) considered the next generation of USAF accident investigations and compiled SD data during 1991-2000 as shown in Table 2. His report compares the incidence and severity of SD with another tragic source of mishaps: loss of consciousness induced by excessive G forces on the pilot (known as G-LOC). While the number of mishaps is decreasing, the number of SD incidents as a percentage of the total is clearly increasing, as seen in these two tables.

Table 2. Comparison of SD to total Class A mishaps and G-LOC from 1991-2000 (adapted from Davenport, 2000).

	Total	% G-LOC Related	**% SD Related**
Mishaps	323	3.5%	**20.2%**
Costs	$5.5B	$174M	**$1.4B**
Fatalities	310	2.5%	**19.4%**

[4] In Canadian terminology, "Category" is used instead of "Class."

The inability of pilots to accurately and intuitively perceive aircraft position without reliance upon visual cues (from flight instruments or the outside world) is a major crux of the aviation mishap problem. Maintaining spatial orientation cannot be done in present-day flight operations unless one is attending to the appropriate visual cues. Unfortunately, many of an aviator's distracting secondary flight tasks are also of a visual nature so continuous attention to one's spatial orientation cannot be maintained using current visual displays. Furthermore, attention can also be diverted to non-visual sources as well (Wickens, 2002), for example the distraction of voice communications or problem solving. Holmes et al. (2003) identify "distraction/task saturation" as the fifth most important factor in their list of causes of spatial disorientation. The problem concerning the allocation of limited attentional resources is compounded by the fact that attentional resources will be drawn to more natural and salient body (vestibular) cues concerning orientation, which in the environment of flight are not veridical. In other words, the problem of SD in flight is not caused merely by attentional limitations; rather, the problem is the formation of an incorrect, yet persuasive, subconscious tendency to rely upon vestibular orientation cues.

A tendency not to recognize hazards during moments of distraction has been noted by SD researchers. The typical SD mishap occurs when visual attention is distracted from the aircraft's orientation instruments and the horizon is not visible or not being monitored (McGrath, 2000). The majority of SD mishaps are related to Type 1 or unrecognized SD. Specifically, 100% of U.S. Air Force SD mishaps during 1990-91 were categorized as Type 1 SD (Lyons et al., 1993). In contrast, relatively few SD mishaps were attributed to SD that was recognized (Type 2) or SD that was completely incapacitating (Type 3).

In years past, the aerospace community came to realize that "pilot error" was not a sufficiently specific description for the cause of a plane crash. Now we must avoid the temptation to consider our job complete when we have identified some general human psychological state as the cause of an accident. As Lyons et al. (1994, page 152) have said concerning SD mishaps: "...if both an attention deficit and SD are part of the chain of events leading to an accident, each should be separately identified as a causal factor if elimination of either would have prevented the accident." This advice makes very good sense in the short term. In the long term, what is needed is to incorporate separately tabulated factors into a model that can accurately predict the amount of variance accounted for by each factor contributing to human error in flight. This requires an initial commitment to differentiate factors that are usually aggregated *a priori*.

In a retrospective survey of SD-related USAF flight accidents, Davenport (2000) found that between 1991-2000 fighter-attack aircraft had the greatest incidence of SD. The overall incidence of SD in the USAF per 100,000 hours of flight averaged about 0.31 during this time; whereas for fighter-attack aircraft the rate averaged about 0.58.

Summary

Accordingly, for our Phase I effort, the F-15 and the F-22 are the platforms of choice. They are the USAF's primary fighter-attack aircraft. Their speed, agility, and terrain following capabilities make them good candidates for inducing profound SD. Our Phase I modeling, simulation, and countermeasures aiding efforts enable progress on other illusions and aircraft during our Phase II work, or in work by other researchers who can use our approach as a quick and effective means to evaluate concepts without the costs and risks of flight tests.

II. Physiology

Major Ocker and Lt Crane...pulled...tobacco pouches over the heads of the pigeons as a blindfold and tossed them out of the cockpit of their biplane. They discovered that the pigeons first flew around aimlessly in spirals but eventually spread their wings into a dihedral shape and floated safely to earth. This elated the investigators with the hope that humans also could navigate 'blind.'

Adapted from Ercoline, 1997

Ocker and Crane were encouraged to discover that if birds did not panic and crash to their deaths when deprived of vision during flight but instead safely glided to the earth, then perhaps humans could learn to rely on other senses to land safely as well. Had they realized that birds evolved in the 3D world of flight, whereas humans evolved from ground dwellers, they might not have felt so enthused. Birds have had eons to evolve in the 3D world of flight motions; humans have not. The observations and subsequent tests of Ocker and Crane during the second decade of human flight led to the development of rudimentary turn and bank instrumentation for non-visual flying. Soon thereafter, Jimmy Doolittle demonstrated blind solo flight, from take-off to landing, and the Army Air Corps made instrument flying a required experience of novice pilots. Students in the 1930s graduated from this training with a certificate from the unofficial "institute of the blind" (Ercoline, 1997).

Overview

This chapter describes the physiological difficulties that human sensory systems, which evolved in an earth-bound space, experience in the aerospace environment. Although SD responses might be considered as due to the inadequacies of human sensory abilities, they are, nonetheless, normal responses to the 3D flight environment. This chapter also describes the motion and gravity sensing systems of humans – primarily the visual, vestibular, and proprioceptive senses – and evaluates how these senses can create the illusions that occur in flight.

Neurophysiological Bases

All organisms live in a 3D and gravitational world. Sensory, neural, and motor mechanisms have evolved in individual species for the representation, coding, and control of spatial behavior. Because we are constantly moving in our environment, we need accurate information about the motion of objects relative to our own position or motion. When human motion includes the third dimension of altitude, we can encounter problems with spatial disorientation, because our species evolved on the ground (or swinging from trees), where vertical orientation was not in doubt.

Of all the human senses involved in spatio-temporal orientation, vision is the most important, particularly during flight. Even for Visual Flight Rules (VFR) training, private pilots are routinely trained in how misleading their reliance upon vestibular or proprioceptive cues alone can be during flight. Such flight training "under the hood" compellingly illustrates SD susceptibility.

The vestibular system provides secondary cues to the visual system in contributing to our awareness of linear and angular acceleration and in helping the eyes to focus on an object. The proprioceptive system is an integrated network of neural sensors in the skin, and in skeletal joints that provides cues to the vestibular and visual systems about limb movements in space. The other senses are only peripherally involved in a human's sensation of orientation and motion, if at all, and will not be considered in the following discussion.

Visual System

The eyes, the most important source of motion information to the human brain, send pictures to the pilot's brain about the aircraft's position, velocity, and attitude relative to the ground. The overwhelming belief in visual cues over those from other senses, when there are sufficient visual cues is called *visual dominance*. Visual cues are more than adequate for spatial orientation on clear days in VFR conditions with a well-defined horizon. But, when visibility is poor (e.g., during night flying, or in IMC), pilots can experience SD illusions. Even on a clear VFR day, the eyes can "play tricks" (e.g., runway and approach illusions).

Vision is most acute at the macula located in the foveal region of the retina in the back of the eye. Figure 1 shows the concentration of rods and cones, the structures that convert ambient light energy into the electrical activity of the nervous system. Oculo-motor muscles attached around the eyeball allow our eyes to focus light on the macula for our sharpest and clearest vision. This high-acuity area is called *foveal vision,* and is distinguished from *peripheral vision,* which lets us see movement and objects about 180 degrees from the center of our visual field. Peripheral vision lets us know we are in a fog bank, for example, while foveal vision enables us to peer through a hole in the fog looking for a runway.

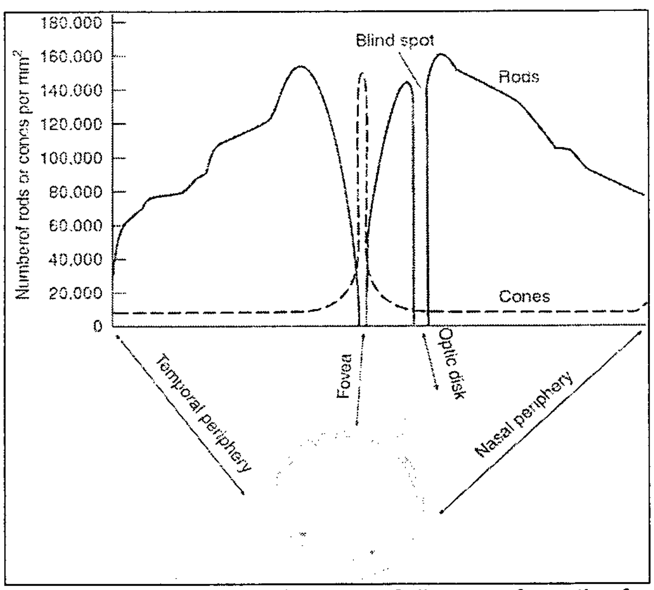

Figure 1. The number of rods and cones as a function of distance from the fovea (Sekular and Blake, 2002, pg. 70).

Detection of the motion of objects and self-motion are so important that motion in the visual field is analyzed by a special pathway of the visual system (Livingstone & Hubel, 1988; Kandel, 1991; Ungerleider & Haxby, 1994). According to current views, multiple visual areas of the cerebral cortex receive a *ventral* stream of information for object vision, and a *dorsal* stream for spatial vision and motion (Ungerleider & Haxby, 1994). Using PET-fMRI scanners to measure changes in regional cerebral blood flow in response to visual stimuli, studies with humans have shown that the ventral stream provides information about objects (the "what" is being seen), and the dorsal stream provides information on spatial vision or motion ("where" the object being seen is located) (Ungerleider & Haxby, 1994; Haxby et al., 1994; Wandell, 1999).

Sensing and controlling motion is now recognized as a specific and complex process in spatial orientation behavior. According to recent studies, when people move through their environment, the visual world *streams* around them, generating motion on the photoreceptors of the retina, and this so-called *optic flow* provides the initial and compelling information for self-motion (Duffy & Wurtz, 1995; Warren & Wertheim, 1990). Although vision provides the dominant information for motion in humans, convergent information from vestibular and kinesthetic systems must also be integrated by the brain to provide a more accurate and complete internal neural representation of movement and navigation in 3D space (Brandt, 1997; Lappe, 1997; Dieterich et al., 1998). According to recent studies, this convergent multisensory information about motion may also create a *spatial cognitive map* along with head direction neurons and so-called *path-integration* neurons, which serve to detect body displacement and navigation in 3D space (Berthoz et al., 1995).

An important distinction in the visual system is that between *focal* and *ambient* vision (Previc, 1998, 2000a; Weinstein & Wickens, 1992). The distinction parallels that between the ventral and dorsal streams, and between the foveal and peripheral vision, but is not identical. In particular, the foveal-peripheral distinction is purely defined in terms of retinal region, whereas the focal-ambient distinction is functionally defined. Focal vision, which is primarily foveal, is used for object detection and recognition, whereas ambient vision, which often includes large peripheral regions, is used for perceiving optic flow and orientation, and hence is critically involved in perception of ego-motion (Warren & Wertheim, 1990; Previc, 1998). There is some indication that the two visual systems are capable of parallel processing (Weinstein & Wickens, 1992). In terms of spatial orientation in the cockpit, it is assumed that a pilot's reference to the true horizon, extending broadly across the visual field, is employing ambient vision, whereas a distinct visual fixation upon the attitude indicator is probably more likely to rely upon focal vision (Previc, 2000a).

Vestibular System

The parts of the vestibular system that we will focus on are the semicircular canals, and the otoliths or vestibular sacs in the inner ear (Figure 2). The semicircular canals are filled with fluid that indicates bi-directional rotation in the pitch, roll, and yaw axes via the cilia, or hair cells, within each canal. The canals are actually accelerometers that sense changes in velocity.

Unlike the sense of vision, the vestibular system does not play a marked role in conscious awareness of posture and self-movement (Goldberg et al., 1991; Kelly, 1991). This is referred to as the *vestibular suppression* of motion sense (due to the subservience of the vestibular system to the visual system). The vestibular system provides the neural mechanism for vertical orientation, independent of movements of the head and body, and for balance, during motion. Normally, visual-vestibular interactions are critical during motion. More specifically, the basic functions of the vestibulo-ocular reflex (VOR), a three-neuron arc, are: to stabilize the visual world; to provide continuous visual and vestibular information about the motion of the eyes, head, and body for eye-hand coordination; and, for body posture (Kelly, 1991). Figure 3 shows the role of the semicircular canals in the three dimensions of flight. The otoliths, connected to the base of each semicircular canal, respond to linear accelerations and decelerations.

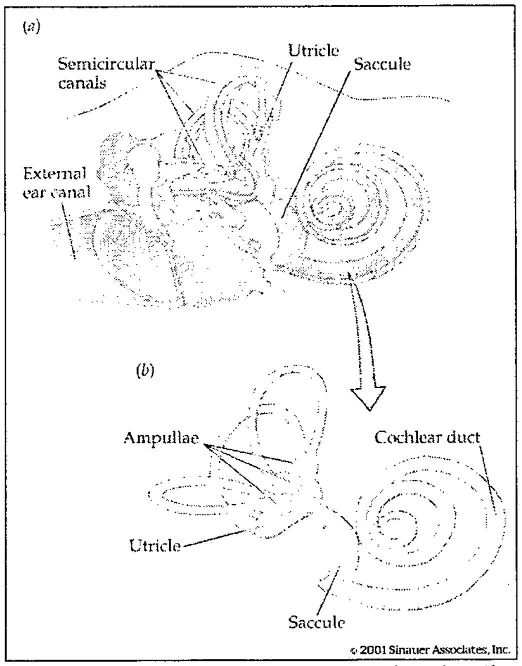

Figure 2. The structure of the outer, middle and inner ears showing the location of the semicircular canals (Rosenzweig et al., 2002, pg 67).

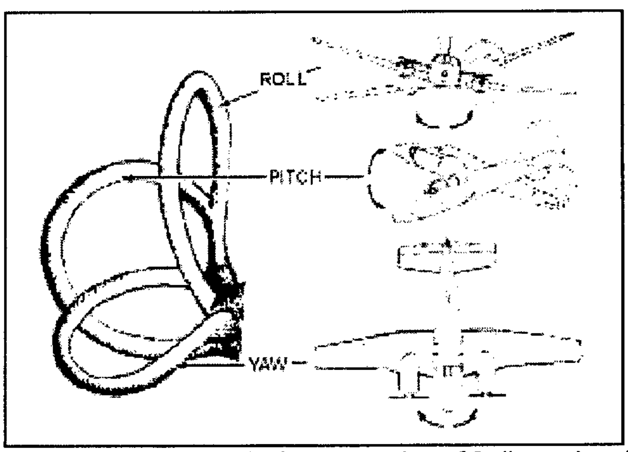

Figure 3. The role of the semicircular canals in the perception of 3-dimensional motion (US Army Field Manual, 2000).

The vestibular system has a long phylogenetic history in mediating orientation to gravity in spatial behavior (Howard, 1986). However, until recently, it has appeared primarily as a silent partner in regulating eye and head movements and particularly in spatial cognitive memory of self-motion, or body linear displacement in 3D space (Berthoz et al., 1995; Baloh & Honrubia, 1990). Normally, vestibular sensations do not produce conscious awareness of space and gravity unless they are in conflict with information from visual and proprioceptive cues.

At rest, the semicircular canals are shown as in Figure 3 and no motion is sensed. As rotational motion occurs, the cilia (hair cells) in the canals bend in response to the relative motion between the canal walls, to which the cilia are attached, and the fluid within the canal. The fluid's inertia provides initial resistance and bends the cilia, which informs the brain of the acceleration axis and the magnitude of angular acceleration. After undergoing sustained and constant angular motion, however (e.g., continuous yaw in a standard rate turn), the fluid within the canals begins to rotate at a velocity corresponding to the body and head. As a consequence, there is no longer relative motion between the cilia and the fluid within the canals, the cilia are not bent, and so no sensation of motion is sent to the brain. This phenomenon is called "washout" and has important implications for spatial disorientation. This washout occurs after approximately 10-15 seconds of sustained rotary acceleration (Gillingham & Previc, 1993).

Another important term to SD research is Mulder's constant (DeHart & Davis, 2002), which describes a threshold below which accelerations are not sensed by the human vestibular system. Mulder's constant is 2° per second, which makes it appear as a velocity, even though it is actually the product of an acceleration and that acceleration's duration. The best way to illustrate the meaning of Mulder's constant is with a few examples:

1. If a person experiences an acceleration of $1°/sec^2$ for 1 sec, he or she will probably <u>not</u> sense that acceleration because the product (1°/sec) does not exceed Mulder's constant.
2. If the same acceleration occurs for 3 sec, however, it <u>will</u> likely be detected (because the product, 3°/sec, exceeds Mulder's constant).
3. Even a large acceleration of $10°/sec^2$ will <u>not</u> be felt, if its duration is less than 0.2 sec. The same acceleration will be felt, if its duration is 0.2 sec or greater.

It is important to note that not all humans have <u>identical</u> thresholds, but Mulder's constant is a good generalization across a population of people. Equally important is the caveat that not <u>all</u> acceleration durations above Mulder's constant will be sensed. Distractions, fatigue, and other physiological reasons may exist to make a person oblivious to acceleration durations exceeding Mulder's constant. It is a good start, though, for any SD modeling effort, as discussed in Chapter IV.

While the semicircular canals sense rotary motion, the otolith organs sense linear acceleration. Here, in the presence of linear acceleration, the cilia within the linear otolith organs will bend backward, opposite to the direction of acceleration. This angle of bend, relative to the orientation of the organ, signals the degree of acceleration. The orientation of the cilia is as affected by gravitational force as well as by accelerations (Howard, 1986). Hence a linear forward acceleration will produce the same vestibular sensation as a tilt backward, producing the phenomenon of the *somatogravic illusion* (Gillingham & Previc, 1993; Tokumaru et al., 1998), in which pilots who execute a rapid acceleration (for example, on a missed approach) may incorrectly perceive a pitch-up motion.

The vestibular organs have been the focus of many past efforts to understand the SD that pilots experience during flight. The vestibular organs are important because they constitute the key sensory modality specifically evolved to detect acceleration of the head in inertial space, yet they are not designed to provide vertical body orientation or sustained acceleration information within the unusual sensory-motor and force environments that occur in flight. However, pilots receive training about illusions caused by vestibular-visual conflicts and are taught to believe their aircraft instruments if they experience such illusions.

Illusions

Spatial disorientation accidents have been referred to as those in which the pilot crashes because the seriousness of the situation does not become evident until it is too late. There are numerous, well-documented illusions that are generated by visual-vestibular conflicts. This section will describe some of the kinds of illusions that result from the unique environments produced by human flight.

Leans

The most common SD illusion in flight is *the Leans* (Holmes et al., 2003; Benson, 1988), which entails an erroneous feeling of roll. A typical case occurs in the following scenario (Gillingham & Previc, 1993): In IMC, the pilot has very slowly entered a turn, perhaps unknowingly, at a sub-threshold rate of less than 2°/sec (i.e., below Mulder's constant) so that the semicircular canals provide no sense of rotation. If the pilot then becomes consciously aware of the aircraft's bank angle (e.g., by looking at the instruments), and intentionally returns the bank to the true level attitude, he or she will now receive a vestibular sensation of an opposite bank. If the pilot continues to rely upon flight instruments to maintain a level attitude, he or she may also *lean* in the orientation of the incorrectly perceived upright (hence the illusion's name). If the pilot does not rely upon the instruments at this point, but rather the intuitive (vestibular) signal of upright, he or she will return the aircraft to its original bank angle. Without awareness and conscious correction, the bank will lead to a gradual pitch down attitude, a loss of altitude, and an increase in airspeed. This side-to-side seesawing process of correction and re-entry may continue until the pilot is so disoriented that recovery to straight-and-level flight is difficult, if not impossible (a Type 3 SD event). This may lead to a progression into a more severe loss of altitude, which ends with ground impact.

Coriolis

The pilot's inability to control the airplane because of spatial disorientation, exacerbated by failure of the primary attitude indicator, night IMC, adverse weather including turbulence and noise from rain, were the cause and contributing factors of the Oct. 2000 crash of a Cessna 335 that killed Missouri Governor Mel Carnahan and all others aboard the aircraft (NTSB, 2002).

The fatal accident that killed Governor Carnahan and his entourage is a classic and tragic example of an SD scenario. We do not know whether it was unrecognized (Type 1) or recognized (Type 2), only that the pilot seemed to pitch down and to the right during his attempt to return and land after an aircraft instrument malfunction shortly after takeoff. The NTSB found that the primary attitude indicator (AI) failed in instrument meteorological conditions (IMC). However, the co-pilot's attitude indicator was working at the time of the crash. The NTSB report indicates that the pilot would logically try to use the co-pilot's AI, located to the pilot's right. Using that AI and then checking his own instruments for heading and altitude, the pilot's head motions, coupled with the airplane's turn back toward the takeoff runway would induce a Coriolis illusion.

The FAA's Airman's Information Manual (ASA, 1995) describes the Coriolis illusion as the "most overwhelming of all illusions in flight" (page 645). It occurs during "a prolonged constant-rate turn that has ceased stimulating the… [vestibular] system," (i.e., washout) when there is an abrupt head movement that creates "the illusion of rotation or movement in an entirely different axis." The resulting tumbling sensation is nearly incapacitating. The Coriolis illusion often results in the pilot's loss of aircraft control, which can have catastrophic results if there is no other pilot to assume control. The power of the Coriolis illusion to deceive is further supported by the finding in a recent survey that it was the most prevalent of those found in 141 pilots attending a course at Randolph AFB in 1997-98 (Sipes & Lessard, 1999).

The Coriolis illusion was selected as one of the prototypical illusions in this project because it is among the most common flight illusions (#5 in the list compiled by Holmes et al., 2003) and is often fatal. It causes overwhelming disorientation and so is an appropriate illusion to combat.

Conclusion

In summary, the physiological circumstances underlying many spatial disorientation illusions are as follows: Aircraft motion, sometimes coupled with head motion, provides illusory vestibular signals to the brain. Normally, when salient visual cues are available, visual dominance will allow the vestibular cues to signal the correct orientation and motion. However, when the visual cues are degraded or missing, the compelling vestibular signals will dominate, and illusions will occur. Knowledge of how these illusions begin and progress provides suggestions for countermeasures, which we address in the following chapter.

III. Countermeasures: Displays & Other Technologies

This chapter describes a multisensory approach to preventing, minimizing, or compensating for pilot spatial disorientation. Since human spatial orientation has such a large visual component, we describe visual displays in some depth. Audio and tactile displays follow, and then an intelligent system approach to applying the various SD countermeasures. All of these technologies fit within a layered approach to combating SD.

Background

We suggest a layered approach to improving pilot attitude awareness and reducing the negative consequences of SD events. Improving current cockpit displays (i.e., head-down, head-up, and helmet-mounted) and incorporating new technologies (e.g., 3D audio, tactile) requires a methodology for integrating and testing all of the salient technologies and techniques to determine which ones are the best at enhancing attitude awareness, preventing SD events, and minimizing the impact of any SD events that do occur. A layered approach begins with pilot training and mission pre-briefings, and extends through improved display technologies and recovery aiding, into post-flight data analyses to better understand, categorize, and track SD events to determine the actual operational effectiveness of the various techniques advocated to improve SD statistics.

Recent research has explored new approaches to addressing SD: better attitude information for head-down, head-up, and helmet-mounted displays; 3D audio displays; and, tactile displays. Which of these approaches, or combination of approaches, is best at reducing SD? Because the potential of each individual technology to reduce SD has not been established (theoretically or empirically), it is difficult to postulate the "best" combination. Rather, it seems that whichever displays are best in a given set of circumstances at helping pilots to recognize and recover from that SD event, then those are the displays that should be used.

How do researchers know which displays are best for different SD scenarios? There is nothing in the current literature to suggest an answer; therefore, it will be difficult to devise the best combination. In fact, a best combination or solution may not be possible for the foreseeable future, due to individual pilot and mission susceptibility, risk factors, and circumstances. But, we can theoretically and empirically determine good combinations of inputs to help combat SD.

Determining the best approach for converting Type 1 into Type 2 SD events should take a human cognition and workload modeling approach. When visual senses are overloaded or deemed unreliable, the audio channel may be useful.[5] A tactile (vest) attitude display may also help, but research into tactile displays is in its infancy.[6] A presently untested sense for SD is the sense of smell. Smells are very compelling and may be useful for Type 3 (incapacitating) SD to help pilots "snap out of it." Such an olfactory system will need sensors to know that the pilot is incapacitated, and the smell used must be penetrating, harmless, and easily carried aboard aircraft.

[5] It is common aviation knowledge that air traffic controllers have talked disoriented pilots through recoveries. The proposed PI has an audiotape of a controller telling a pilot to "release the controls" to recover from a graveyard spiral.

[6] *Vibrotactile transducers: Utilizing tactile displays to improve performance in spatial tasks in aerospace, land and sea environments.* http://www.navysbir.brtrc.com/cap/briefingsadmin/ea.asp.

When the pilot does not recognize an SD event (Type 1), intelligent aiding systems may help. For example, audio recovery instructions have shown some early utility with SD events in simulators.[7] They key is for the aiding system to recognize when SD is causing an unusual attitude or dangerous situation. The emphasis of such systems ought to be on preventing the bad consequences of SD events, since it will be virtually impossible to prevent all SD events due to the normal physiological response to most events that induce SD (as described in the previous chapter).

Consequently, the best approach is a layered one that seeks to enhance attitude awareness and combat SD via multiple techniques: training improvements, operational awareness, better displays (visual, auditory, tactile, olfactory), intelligent automation, and rigorous post-flight SD event analyses to better understand and characterize SD events, which should also indicate the operational effectiveness of the various SD-combating techniques.

Training Improvements

Training can help pilots recognize the types of circumstances that lead to SD so that they will be vigilant for the same or similar circumstances (Gillingham & Previc, 1993). Training also needs to be enhanced and should include classroom discussion, simulator and centrifuge training,[8] and aircraft demonstrations. While there is some risk to aircraft demonstrations, the risk of not doing so is reflected in the rates of SD accidents in military and civil aviation over many decades. Clearly, not all SD event categories could be demonstrated, but a significant cross-section could be. Teaching SD situation recognition is a major contribution to prevention.[9] And, pilots who are more vigilant for SD-inducing circumstances are better equipped to avoid or successfully combat them. It is also important to teach recovery techniques for each SD situation to reduce the occurrences of Type 3 SD events. The most prevalent factor in USAF SD incidents is attention management (Davenport, 2000), a skill that can (and should) be improved with training (Gopher, Weil, & Barakeit, 1994).

Operational Awareness

Pre-briefings could reduce some SD event severity. Certainly, pre-briefings could increase the odds of any SD event being Type 2 rather than Type 1. Since the environmental conditions that increase susceptibility to SD are known, mission pre-briefings will be timely reminders to pilots, thus reducing the likelihood of an SD event being Type 2 or 3. The Indian Air Force has developed a checklist enumerating SD threats, and has even anticipated the increased threat of SD from supermaneuvers, in such aircraft as the F-22, F-35, V-22, and Apache helicopter (Gomez, 2002).

US Air Force statistics about contributing factors to SD incidents point to conditions in which the pilot is highly susceptible to SD. All of this knowledge and experience should be highlighted during mission planning and pre-briefings so that pilots can be vigilant. Weather conditions, moonless night flights over the desert, and night vision goggle (NVG) use, are all known to be

[7] Personal communication with Dr. Kristen Liggett (11/21/02): "…'talking' the pilot through a recovery is something we just recently tried in the lab…. The data is still being analyzed, but…they [the pilot subjects] followed the instructions and had successful recoveries."
[8] There is a new type of simulator for such training; see *Aviation Week & Space Technology*, 12/2/02 issue, pg. 60.
[9] *Preventing disorientation mishaps*. http://www.spatiald.wpafb.af.mil/prevention.asp.

risk factors (Berkley & Martin, 2000). Reminding pilots of the relevant mission risk factors, and what to do if SD occurs, refreshes their earlier training – another important layer in a comprehensive approach to mitigating the effects of SD.

Display Improvements

Because the primary source of information to the pilot is visual, because the visual modality is the most compatible modality for presenting spatial information relevant to attitude (Wickens et al., 1983), and because SD incidents are most prevalent in IMC or at night (when the view of the true horizon is obscured or gone), it is not surprising that a key countermeasure in combating SD is in the design of **effective** visual displays. Sadly, many advances in this direction are lacking, because design has generally focused on providing the necessary information to support spatial orientation, but not on the ideal **format** in which that information should be depicted most naturally or intuitively. One of the major culprits appears to be the focus on using the round dial or "steam gauge" display, even as cockpit displays have evolved to include computer generated imagery, where the electromechanical constraints associated with the round dial are no longer relevant. In the pages below, we discuss some of the display formatting issues and ideas that are relevant for effective support of spatial orientation, in conventional head-down instruments, and in head-up and helmet-mounted displays.

Frame of reference for the attitude indicator

Clearly, in IMC, a pilot's perception of the upright must be supported by a well-designed attitude indicator (AI), which can support the intuitive grasp of the orientation of the horizon. Much of the research on AI design has focused on the question of whether the aircraft symbol or the horizon line should move as a function of aircraft bank and pitch. The conventional design, presenting a moving horizon, is argued to be congruent with the pilot's *mental model* or mental representation of the forward horizon appearing to slant in one direction, which is opposite to the direction of the aircraft's actual bank. Thus, this AI design corresponds to what Roscoe (1968) describes as the *principle of pictorial realism* (see also Wickens & Hollands, 2000; Wickens, 2003).

In contrast, the *principle of the moving part*, also associated with Roscoe's (1968) work, proposes that the moving element on a display should correspond to the element that moves in the pilot's mental model of the aircraft, and should move in the same direction as that mental representation. Because the pilot's mental model represents the aircraft moving in a world that is stable (Johnson & Roscoe, 1972; Kovalenko, 1991; Merryman & Cacioppo, 1997; Previc & Ercoline, 1999; Previc, 2000a), this principle suggests that the aircraft should be depicted as the moving element on a display, and, for example, when the aircraft climbs or pitches up, this element should move upward. The moving horizon of the attitude indicator in Figure 4a violates this principle, since the moving element (horizon) moves upward to signal that the aircraft is pitching downward, and rotates to the right (or left) to signal that the aircraft is rotating left (or right). To conform to the principle, the airplane should move around a stable horizon, as in Figure 4b.

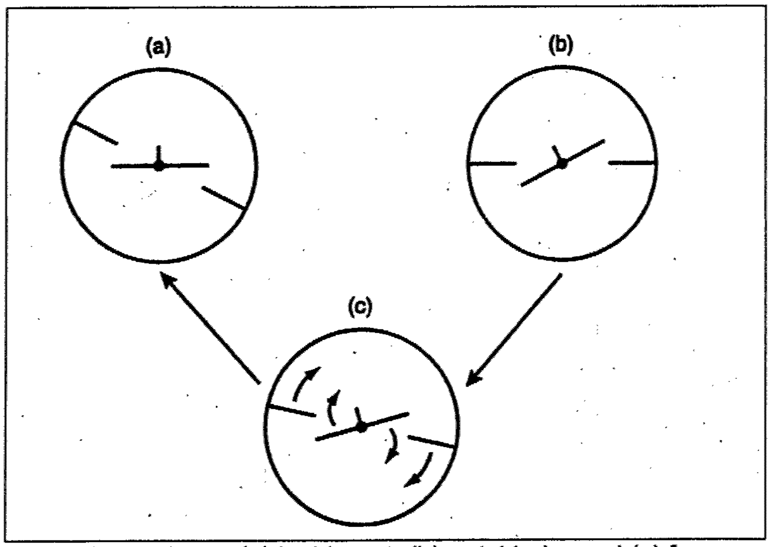

Figure 4. Aircraft attitude displays: (a) inside-out, (b) outside-in, and (c) frequency-separated. All displays show a left bank. Low frequency return to steady state is indicated by arrows in (c) (Wickens & Hollands, 2000, pg. 137).

However the conventional design to configure the AI as a moving horizon, rather than as a moving aircraft, is one that can be argued to better satisfy the principle of pictorial realism, since, when the pilot looks outside, the moving horizon display better corresponds with what is seen looking forward from the cockpit. Roscoe (2002) has argued that the consequences of such violations of the principle of the moving part, are possible confusions leading to spatial disorientation, when, for example, a downward display movement is incorrectly interpreted as a downward aircraft movement; or, when a clockwise rotation of the horizon on the AI, is misinterpreted as a clockwise rotation (right bank) of the aircraft (Roscoe, 1968; Kovalenko, 1991). If these misinterpretations are followed immediately by the correct-appearing (but actually backward) control corrections, then the off-attitude state of the aircraft will be amplified, rather than nullified, exacerbating the situation.

The results of earlier studies by Roscoe and his colleagues (Beringer, Williges, & Roscoe, 1975; Roscoe & Williges, 1975), and Kovalenko (1991) comparing moving aircraft with moving horizon attitude indicators has led to considerable debate about the ideal configuration of this important instrument (Previc & Ercoline, 1999), to conform to the one principle (moving part) or the other (pictorial realism). A review of the literature suggests that the moving aircraft display is more effective than the moving horizon display for novice pilots with no prior experience on either, and is no less effective, even for experienced pilots who have had prior flight experience with the moving horizon display (Previc & Ercoline, 1999; Cohen et al., 2001). The advantage of the moving aircraft will be amplified in IMC (where there is no true horizon visible), and diminished in VMC (Merryman & Cacioppo, 1997; Gallimore et al., 2000).

The overall benefit for a stable horizon may result, in part, from the pilot's reflexive tendency to orient the head to the outside horizon as the airplane banks (i.e., to visually stabilize the horizon), a phenomenon called the *opto-kinetic cervical reflex* (OKCR) (Merryman & Cacioppo, 1997; Previc & Ercoline, 1999; Previc, 2000a; Smith et al., 1997). If the head rotates counter to the airplane when the latter banks, so that the line connecting the two eyes parallels the horizon, then the eyes will actually see a stable horizon as the airplane banks, and those aspects of the airplane that are in the visual field will be seen to rotate; that is, a direct perception will be one of a moving airplane, corresponding to what is seen on a moving airplane AI. While the OKCR is a phenomenon that is primarily manifest in VMC, when the true horizon is visible (Gallimore et al., 2000), the underlying tendency to orient the head to the perceived upright, seen so strongly when the horizon is visible, is also manifest when the horizon is inferred from vestibular feedback in IMC, as manifest in the Leans, discussed in Chapter II.

The role of OKCR in supporting the moving aircraft bank perception, might suggest that this world-referenced frame (moving aircraft) is more pronounced in bank than in pitch, which is the case (Merryman & Cacioppo, 1997; Patterson et al., 1997; Smith et al., 1997).

While the debate is not likely to lead to the redesign of the head-down attitude indicator with a moving aircraft, it is possible that that certain design solutions can capture elements of both principles. The concept of a frequency-separated display (Figure 4c) is one such solution, in which rapid (i.e., high frequency) rotation of the aircraft, as when entering a turn, leads to a rotation of the aircraft symbol on the AI in the same direction as the true rotation of the aircraft. Then, after the aircraft stabilizes at the new bank angle and holds this steady state for some time (i.e., low frequency), the AI horizon line gradually rotates to correspond to the true horizon, and the aircraft symbol, in turn, rotates back to an upright position. The reverse control, implemented to bring the aircraft back to straight and level, will reverse this sequence of motion.

Another solution is the 3D *pathway display*, or highway in the sky (HITS) display. This display provides a prediction of the future location of the aircraft, which conforms to the principle of the moving part, even as the attitude indicator itself conforms to the principle of pictorial realism (Fadden, Ververs, & Wickens, 2001; Alexander, Wickens, & Hardy, 2003). That is, a right bank of the aircraft will initiate an immediate rightward movement of the predictor symbol on the display, creating an immediate and intuitive perception of a right turn (i.e., bank), even if the artificial horizon rotates to the left. Roscoe (2002) has argued that such a design may mitigate the concerns for roll reversals.

Finally, other research on horizon representation has focused on a moving horizon format, but distributed across a wide range of space in the cockpit, so that it can be perceived not just with focal and foveal vision on a small attitude indicator, but also with ambient vision across a wide range of the visual field, making it more resistant to attentional tunneling, just as we view the normal horizon for orientation information (Previc, 2000a). One means of doing so is through laser projection of the so-called *Malcomb Horizon*, projected in space from behind the pilot (Gawron & Knotts, 1984). Current technological limitations have prevented these from realizing success in flight tests (see Stokes, Wickens, & Kite, 1990 for a review). A second way of accomplishing this has been proposed as a *Background Attitude Indicator* (Liggett, Reising, & Hartsock, 1999), which presents the horizon spanning across smaller panel displays. Both of these techniques allow perception of the horizon as the head is rotated. A third approach is to present the horizon on a helmet-mounted display (HMD). We consider this issue below in the broader context of presenting overlaid information on either an HMD or a head-up display (HUD).

HUDs & helmet-mounted displays
The issue of the frame of reference for the attitude indicator on a see-through display (HUD or HMD) adds additional complications. For the HUD, the problems of motion incompatibility between a moving aircraft display, and the moving horizon seen outside will be amplified in VMC, relative to a head-down presentation, because the two different motion frames will be viewed directly superimposed on each other. For the HMD, which we discuss in some detail, the problem of frame of reference for attitude representation and spatial disorientation become even more complex, when the HMD is used for off-boresight viewing.

The design of the HMD (Melzer & Moffitt, 1997; Wickens & Rose, 2001) must consider two general human factors issues, which we shall address below:

(1) What is the advantage (or cost) of presenting information on an HMD, rather than on a conventional fixed display?
(2) How should the imagery on the HMD be presented?

It turns out that the answer to the second question greatly depends on both the task and the frame of reference (FOR) with which the imagery is presented, and so we shall focus on three different frames of reference for presenting HMD information. It further turns out that the choice of an HMD to present information (and the choice of a particular FOR), also generates certain *spawned costs* analogous to those encountered when choosing a 3D (HITS) display.

The HMD has two distinct benefits relative to the HUD:

(1) Allowing continuous viewing of instrumentation across a wide range of head movements (in particular, when engaged in off-axis viewing). This potentially allows instant access to attitude information, and can therefore potentially mitigate concerns of attitude awareness.
(2) Enabling a much wider range of visual space within which conformal imagery can be displayed.

These two benefits are generally associated with different frames of reference of HMD imagery (Wickens et al., 2001). Specific images (usually non-conformal) which are viewable independently of the orientation of the head, are said to be *screen-referenced*, since the coordinates upon which those images are drawn, are defined exclusively by X-Y coordinates on the HMD surface. In contrast, conformal imagery on an HMD is said to be *world-referenced*, since it overlays distinct positions in the world and its location on the screen will be contingent upon the momentary orientation or movement of the head. World referencing on a see-through HMD creates what is known as *augmented reality* (Milgram & Colquhoun, 1999). World referencing on an opaque HMD, while not discussed in detail here, can be used to create the *virtual cockpit* (Barfield & Furness, 1995), which might be used for training purposes, or for flying remotely piloted vehicles.

A schematic representation of the view, seen by pilots in a screen-referenced and a world-referenced HMD is shown Figures 5a and 5c, for pilots who are looking to the right and see the indicator of their aircraft in a right bank. In addition to the world- and screen-referenced frames shown in Figure 5, HMDs allow depiction of a third frame of reference – the aircraft, or *aircraft-referenced* symbology. Here the symbology is drawn at a fixed location relative to the axis of the aircraft. An example would be a set of flight instruments that are depicted to appear at the normal location of the HUD. This view is shown in panel Figure 5b, representing the turning head.

While the distinction between these three frames of reference for HMDs is every bit as critical as is the distinction between conformal and non-conformal imagery for HUDs, there are in fact very few studies that have contrasted them, to allow conclusions of "which is better" to be drawn. Taylor and Kuchar (2000) compared screen-referenced to aircraft-referenced symbology for attitude recovery for fighter pilots. Their experiments required pilots to look off axis with the HMD while at an unusual attitude, and, upon hearing an auditory cue, immediately recover to wings-level flight. The investigators found that the airplane-referenced display imposed a delay in recovery, as the pilots needed to return the head to a forward viewing position before initiating the maneuver, whereas with the screen-referenced display, pilots could (and did) initiate their recovery before rotating their head forward.

Herdman and colleagues (2000) also compared a screen-referenced HMD with an aircraft-referenced HMD and contrasted these with a mixed display containing both. Their rotorcraft pilots engaged in a forward flying maneuver. In the mixed display, attitude information remained aircraft-referenced, so that it would be conformal with the true horizon when the pilot looked forward, but drop out of sight (like a conformal HUD) when the pilot looked off axis. The investigators found a general advantage for screen-referenced information. In the mixed condition, the presence of both kinds of symbology on a single display, moving differently as the pilot's head rotated, did not appear to disrupt performance, because of the ability of pilots to cognitively separate the two domains on the basis of motion cues.

In both of the above experiments, aircraft-referenced attitude information was also configured to be partially conformal with the outside world, in the sense that, when the pilot looks forward and varies attitude, the behavior of the instrument horizon would mimic that of the true horizon, as would be the case of a partially conformal HUD. This raises the question as to whether such conformal but screen-referenced displays (like the AI shown in Figure 5a) would be disruptive to aircraft control if they are viewed off axis; that is, a contrast between panels (a) and (c) in Figure 5, as these would be used for attitude control. Both panels depict a plane banked to the right; however, the conformal world-referenced horizon symbol shown in Figure 5c depicts the horizon as it would look to a pilot looking outward along the right wing of a right-banked aircraft. Again, there is little data to compare the efficacy of these two frames of reference.

Haworth and Seery (1992) compared the two frames, across a range of typical tasks for the rotorcraft pilot in a full mission simulation, while pilots looked off-axis, as they were engaged in search for targets and maintaining awareness of terrain features. They found that neither display was terribly effective for unusual attitude recovery during off-axis viewing with both showing a large number of initial control actions in the wrong direction; the world-referenced display showed more errors. In the world-referenced frame (Figure 5c), it is easy to see how vertical movement of the horizon line, signaling a bank change, could be misinterpreted as a pitch change. However, Haworth and Seery (1992) also found that for tasks involving perception of the simulated outside world (e.g., altitude and terrain estimation, contour flight), the world-referenced symbology either supported better performance or was more favorably rated than was the screen-referenced symbology. This makes sense, given the total *conformality* (scene linking) of the world-referenced attitude with the outside world view, a particular advantage in low-level flight.

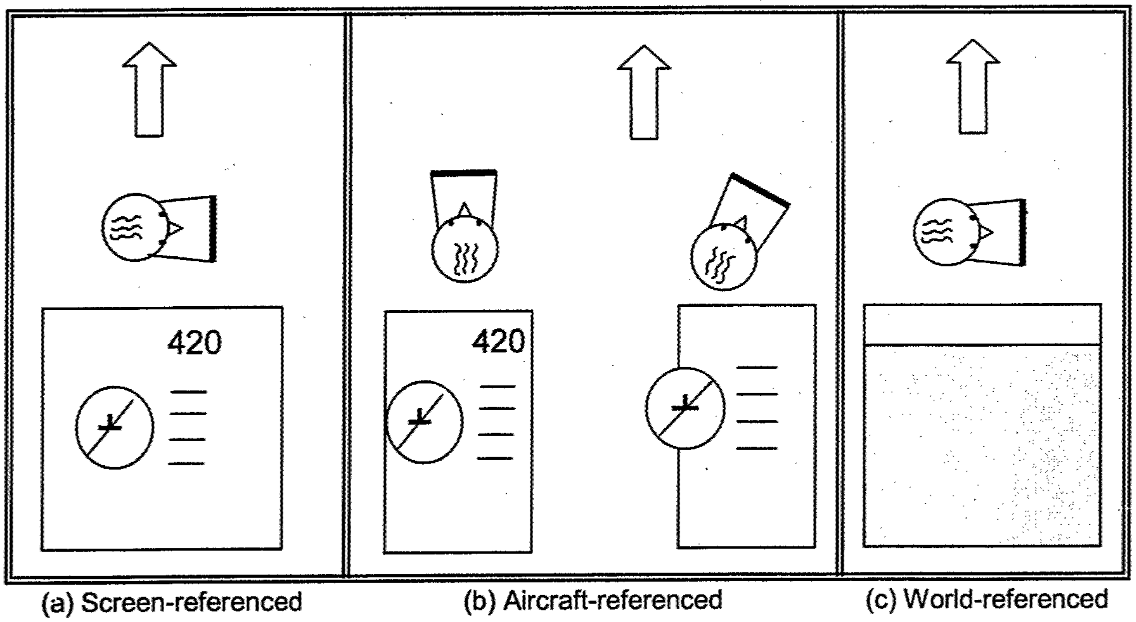

Figure 5. Four views depicting three different frames of reference on a helmet-mounted display. The arrow at the top shows the direction of flight and axis of the aircraft. The figures in the middle row show the orientation of the head and the HMD. The figures on the bottom show the view on the HMD screen of an aircraft banked to the right. (a) Screen-referenced. (b) Aircraft-referenced (two views as the head turns). (c) World-referenced. The gray band represents the ground and the white band represents the air. The dividing horizon line would move downward if the pilot returned to a wings-level attitude.

The two slightly contradictory trends (one favoring each frame) observed by Haworth and Seery (1992) are consistent with two emerging findings. First, as we described earlier, the world referencing of the conformal symbology set may facilitate the division of attention between the instruments and the outside world, eliminating any visual conflict between the two visual sources, and, like scene linking, serve to better *fuse* the two views (Levy et al., 1998; Fadden et al., 2001). This fusion would not occur as a result of the conflicting motion patterns when the screen-referenced symbology is viewed off-axis. Second, there is some evidence that the interpretation of displayed motion when viewed off-axis, is easily and automatically mentally transformed to a forward viewing axis, just as the head itself naturally rotates to the canonical forward view relative to the trunk (Wickens et al., 2003; Worringham & Beringer, 1989; Previc, 1998). Hence, a display that presents motion that would be un-transformed when viewed in a forward orientation should be more rapidly and correctly interpreted, consistent with the findings of Haworth and Seery (1992) favoring the screen-referenced symbology for attitude recovery.

A study by Cohen et al. (2001) is also consistent with the latter conclusion. Although the investigators did not employ a true HMD, they positioned a standard screen-referenced attitude indicator in either a forward view or in a 90-degree off-axis viewing plane, relative to the orientation of the pilot's trunk (and control axis). For both skilled pilots and naïve non-pilots Cohen et al. (2001) observed no cost to off-axis viewing in a standard (pitch and roll) tracking task. That is, even when the instrumentation was placed off axis, pilots were able to mentally rotate the frame of reference to a forward view automatically with no cost. This equality across viewing locations was observed independently of whether an inside out (moving horizon) or outside in (moving aircraft) frame was employed. However, the investigators also examined a third attitude indicator, which was a side view display somewhat analogous to the view shown in Figure 5c (although presented as a moving wing and fixed horizon, rather than the moving horizon display shown in Figure 5c). This depiction corresponds in some respects to the world-referenced attitude indicator examined by Haworth and Seery (1992), in that both depict *vertical* (rather than rotational) movement on the display, as the pilot views a change in bank while looking 90 degrees off axis.

Consistent with Haworth and Seery's finding regarding attitude recovery, Cohen et al. (2001) also observed a cost to this world referencing of attitude, relative to the screen (or aircraft) referencing condition. In contrast to the experiment of Haworth and Seery (1992), this study found no benefit at all for the world-referenced display. But, correspondingly, the pilots in Cohen et al.'s studies (2001) flew entirely in an instrument environment with no outside view, so that there was no source of perceptual conflict with the outside world, and no possible benefit to scene linking of the outside world in attention division. Such a conflict might otherwise have been observed in a side view, screen-referenced attitude display and indeed this conflict imposed the penalties observed by Haworth and Seery (1992).

Display Symbology

Attitude displays (head-down, head-up, and helmet-mounted) have symbology to help recognize unusual or undesirable attitudes that usually result from SD (cf., Figure 6). Such symbology should be enhanced based upon the latest research results (Previc & Ercoline, 1999; Meehan, 2001). In particular, the impact of NVGs is ripe for further research and how to accommodate the visual limitations caused by NVGs (Berkley & Martin, 2000).

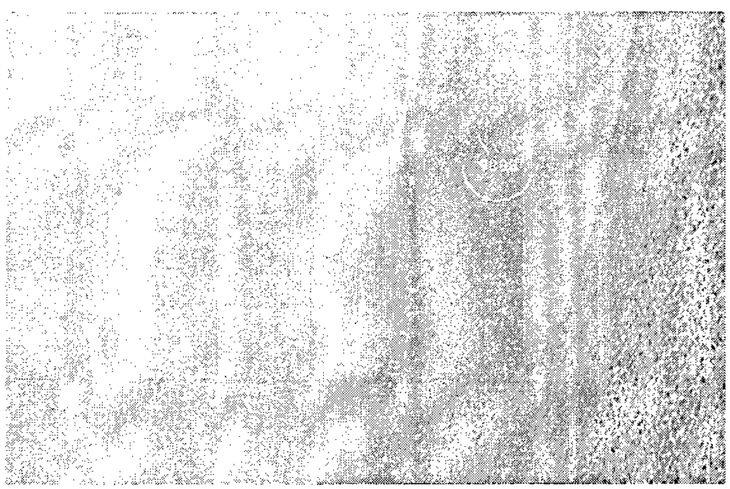

Figure 6. Military standard HUD symbology.

Recent research results (e.g., Bainbridge, 1999; ISO, 2002) suggest the development and testing of a display icon that uniquely conveys the existence of an unusual attitude and what to do about it. We propose that this icon conform to characteristics that make it easy to detect, interpret, and act upon without confusion or control reversal errors (CREs). Such a display icon should be a unique simple geometric shape that portrays the relevant information in an easily understood format (Bainbridge, 1999).

Using the principles espoused by Bainbridge (1999) and our earlier modeling criteria, the icon should portray pitch and bank in a way that makes it clear what the attitude is, and what pilot must do to recover from an unusual attitude. Figure 7 illustrates our concept for an icon to be displayed on head-down displays (HDDs), HUDs, or HMDs. Previc's (1998) theory of visual fields suggests that the ideal location is in upper-right quadrant of any display.

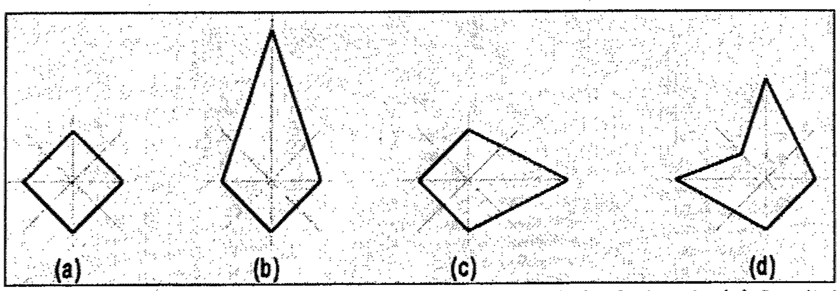

Figure 7. Attitude icon: (a) 0° pitch, 0° bank; (b) 90° nose-up pitch, 0° bank; (c) 0° pitch, 45° right bank; and, (d) 45° nose-up pitch, 45° left bank.

Advances in panoramic HDDs, HUD symbology, and HMDs beg the question of how to best use each of these displays to enhance pilot attitude awareness and to combat SD. Ercoline, a leading SD researcher, has challenged the need for HMD attitude symbology, and suggested a study using 4 experimental objectives: agree on symbology across the services; agree on flight tasks; develop a protocol; and, establish research facilities and staff (Ercoline, 1998). The point is that there is not an expert consensus about whether or how to use HMD symbology to prevent SD.

Pilots maintain attitude awareness via their visual scan; but, when SD occurs, the typical feeling is of a conflict between their vision and somatic senses. It feels like their vision is lying to them. Therefore, relying primarily on visual display cues to recover attitude awareness is probably less effective than using a combination of multisensory displays. Recent research has explored using auditory and tactile senses to combat SD. This recent research is laudable precisely because SD accident rates have remained constant during the decades when attitude information appeared only on visual displays. Clearly, a new emphasis is needed. We next examine auditory, then tactile countermeasures for SD.

Auditory Countermeasures

A key feature highlighted in our previous discussion of visual display countermeasures, was the ability of displays to capitalize upon parallel processing, or separate resources, so that, for example, ambient vision could process a peripheral horizon, even as focal vision was involved with other aspects of visual perception (Weinstein & Wickens, 1992; Previc, 1998). Correspondingly, a long history of research on multiple processing resources (Wickens, 2002), has revealed that the auditory modality can process information in parallel with the visual, and therefore the auditory channel should be able to support spatial orientation in an otherwise visually loaded, or visually impaired (e.g., by nystagmus) environment. In making this suggestion however, it should be borne in mind that the auditory modality is inherently less compatible for providing spatial information, than is the visual (Wickens, Sandry, & Vidulich, 1983).

Potentially useful auditory information can be classified into four categories; the first two are discrete/symbolic, and the second two are continuous/analog.

(a) Discrete alerts. This describes the standard advantage of the omnidirectional, and intrusive auditory modality for presenting critical warnings. A sharp sound or single carefully chosen word can warn pilots that they may be experiencing SD.

(b) Verbal commands. Verbal commands can provide effective corrections about what to do to recover from an SD incident, as the verbal modality is well suited for command displays (Wickens & Hollands, 2000), and there are well-documented successes in aviation for such commands, such as the "climb climb" resolution advisory in TCAS, or the "pull up" command of the Ground Proximity Warning System (see Wickens, 2003 for a review). In both cases, the commanded verbs directly signal an action, and the verbal modality can break into a visually saturated processing stream. It is easy to envision how a simple verbal command of the correction required to pull out of an unwanted attitude could be effective, (e.g., "bank left"), assuming that such a command was offered following the correct inference of aircraft state.

(c) Continuous localization. A fairly extensive body of research has established the ability of auditory tones or sounds to convey information as to the location of their source, by mimicking the central and peripheral acoustic effects of the two ears (Nelson et al., 1998; Begault & Pittman, 1996). Such systems typically employ intensity and phase differences between the two dichotically presented sounds, to accurately signal the azimuth of a perceived sound, relative to the momentary orientation of the head. A very naturalistic or "ecological" signal of head orientation relative to the source of sound can be provided, offering good support in airborne target acquisition studies (e.g., Begault & Pittman, 1996; Nelson et al., 1998; Endsley & Rosiles, 1995). However, an unfortunate aspect of such systems is that they are far less accurate in conveying elevation information than azimuth information. Furthermore, spatial disorientation, as we have noted, is attributed to a failure to appreciate which direction is up, rather than which direction is forward. Hence auditory localization is less perfectly suited for orientation than for location.

(d) Continuous orientation. To provide a continuous signal of which way is up typically requires some non-naturalistic assignment of head orientation to tone pitch and or intensity. In this regard, effective demonstrations of auditory compensatory tracking have been provided by various researchers (Forbes, 1946; Vinje & Pitkin, 1972; Costello, 1976; see Wickens, 1986 for a review). Typical is the assignment made by Vinje and Pitkin, in which the ear in which a tone was presented represented the side of an error (in this case, an attitude displacement from level), while the pitch of the tone represented the magnitude of the error. Such a system would create an increasing pitch tone, as the aircraft rolls to one side or the other. It has been found fairly effective in supporting continuous compensatory tracking, although greater benefits are often realized when the auditory cues are offered redundantly with visual cues, than in a single task auditory environment.

An important feature in designing such systems for SD applications is that the pilot can gain greater information from the time-varying trend of tones and sounds, than from the absolute pitch or intensity levels of such sounds. For example, an **increasing** pitch (or volume) can signal that things are getting worse. But there is no particular **level** of pitch (or volume) that can be used to intuitively convey a particular state (e.g., middle C, or 70 decibels corresponds to 45° of bank). A second issue is whether the direction of a tone (e.g., left or right ear) should correspond to the status of error, or the necessary command to correct the error. Will a rising tone in the right ear intuitively signal that the right wing is rising (and therefore the plane is banking to the left), or the converse? Such a mapping of tone to state must be done consistently and intuitively by the pilot, otherwise control reversals will result (as has been observed for the visual moving horizon display being confusing, as discussed above). The importance of this intuitive mapping is heightened for the SD application, because the usage of any auditory cuing will be required when the pilot may already be in a stressed state, in which non-intuitive mappings are likely to be ignored or misinterpreted (Wickens, 1995).

In summary, audio tones are good as alerts of undesirable states, and audio commands are effective in directing recoveries from unusual attitudes; but tones are not intuitive for orientation cueing.

Tactile Displays

Early research into tactile displays was by Gilson et al. (1975), who described a lever system attached to the control yoke. Their goal was to indicate AOA to pilots via a lever that would push into the pilot's hands to indicate which direction the pilot should move the yoke (push or pull) for the optimal AOA during low speed flight phases (i.e., takeoff, approach, landing). Solomonow et al. in 1977 and 1978 examined human sensitivity to vibrotactile displays, the early forerunners of today's tactile vests. Their goal was to determine appropriate vibration frequency ranges, pulse widths, and body locations for maximum sensitivity and information transfer. Kaczmarek (2000) examined adaptation and stimulus threshold changes with repeated vibrotactile stimuli.

Recent developments include full tactile vests, used to transfer altitude deviation and attitude information (Rupert, 2000; Raj et al., 2000; McGrath, 2000; Rochlis & Newman, 2000; Spence, 2002; van Erp, 2003, Engineering Acoustics, Inc., 2003). Tactile systems are typically used to complement visual or audio displays, not in isolation, because of their lack of comparable sensitivity. Research into this promising display technology is ongoing due to its relative ease of implementation, and early results.

In many respects the creation of tactile displays can match applications a, c, and d of auditory displays discussed in the previous section, and there is, indeed a fairly close correspondence between the two modalities. Tactile stimulation can (a) alert (Sklar & Sarter, 1999), it can (c) convey azimuth location information (for example, a stimulus presented from a belt around the waist), and some sense (d) of orientation (e.g., differential elevation between the left and right sides). Research on tactile channels for orientation however is considerably more sparse than for auditory channels (Rupert, 2000; van Erp, 2003). Both modalities would probably suffer from habituation, and so must be used sparingly and in concert with other sensory inputs.

Display Technologies Summary

Our previous discussion has focused on visual displays, because of the precise spatial information that these can provide. However both auditory and tactile displays offer potential in combating SD (or maintaining spatial orientation), because of their capability of providing information in parallel with an overloaded visual system (Wickens, 2002). Indeed auditory localization displays have provided useful spatial information in orienting toward targets in 3D space (e.g., Begault & Pittman, 1996; Nelson et al., 1998), as well as in continuous tracking (Vinje & Pitkin, 1972; Forbes, 1946; see Wickens, 1986 for a summary). More recently tactile and haptic displays have been explored for similar purposes (e.g., Raj, Kass, & Perry, 2000; van Erp, 2003). While it is clear that information from these displays **can** be processed in parallel with visual processing, thereby potentially exploiting multiple resources, it remains to be seen the extent to which such parallel processing **will** take place in the high stress and workload of spatial disorientation.

New technologies, such as 3D audio and tactile displays can enhance recognition by using non-visual channels of cognition to "get through to" the unaware pilot. Since SD is often triggered by a disparity between visual and vestibular senses, it is wise to stimulate other senses to aid recognition. Audio is an especially compelling input because it tends to override other senses for attention (Wickens, 2002). In addition to the above, we can also consider *verbal* auditory information, such as commands to the pilot on how a control should be moved, or what instruments should be consulted, in order to restore spatial orientation. These too are capable of exploiting the multiple perceptual resources of a visually overloaded (or incapacitated) pilot.

Visual and tactile display enhancements may be less effective during G-induced SD because of vision tunneling and somatic G-force effects (Rochlis & Newman, 2000). Researchers must also consider how to integrate new display ideas with existing cockpit displays, audio, etc. The goal is to use the "best" sensory cues for the particular SD conditions, if the event characteristics can be confidently established.

In conclusion, it would appear that a number of features in both visual and non-visual displays can support the pilots' perception of attitude. For visual displays, many of these capitalize upon ambient vision and the presentation of attitude across a wide range of visual angle. For non-visual displays, they exploit the multiple sensory resources of the pilot. Given other findings in the research literature supporting the advantage of redundant presentation of information (Wickens & Hollands, 2000), it would appear that offering attitude information through redundant channels could be a valuable tool to restoring spatial orientation. In the following section, we suggest ways in which this might be accomplished.

Intelligent Aiding Systems

Intelligent onboard systems that can recognize SD and its causes would provide a huge advantage in the fight against negative SD consequences. Such systems would not only tailor displays to the particular SD event, but could trigger recovery actions, such as synthetic speech to talk the pilot through the appropriate recovery.[10] An even more intelligent system could also initiate recovery without jeopardizing the mission by considering such factors as position relative to

[10] Personal communication with Dr. Kristen Liggett about such an experiment (11/21/02): Audio recovery instructions seemed to be effective and pilots liked it; results not yet published.

enemy airspace, threat warning system inputs, and fire control modes. Triggering an auto-recovery without considering mission impact and pilot intent is unacceptable, except in the most extreme circumstances. Auto-recovery exists on the Swedish Grippen in the form of auto-GCAS (Scott, 1999). However, US pilots distrust auto-recovery systems due to potential errors and the possibility of adversely affecting the mission.[11] Because of the drawbacks of a fully automated system, a pilot-activated system could be an interim step. However, a pilot-activated recovery system would not be effective for Types 1 or 3 SD, by definition. Manual activation would be effective for Type 2 SD events and so should be a part of the layered solution, at least until its efficacy can be proved or disproved.

Extensive research has been done on aircraft state, pilot intent, and hazard monitoring intelligent systems.[12] Such systems would be relatively easier to implement for civilian than for military aircraft, and so can be developed, tested, and certified in the more benign civil environment as a prelude to military systems, if warranted.

Most importantly, an intelligent cockpit system would trigger the SD countermeasure(s) determined to be most effective in any given situation. Due to the likelihood of sensory overload, an intelligent SD Aiding System would apply multisensory countermeasures for redundancy, urgency, and for improving the odds of "getting through" to the pilot. We have already discussed visual, auditory, and tactile displays; one other sensory channel remains: olfactory. An intelligent system could trigger a unique harmless odor (similar to a unique audio tone) that means, "Spatial Disorientation strongly suspected; check your instruments!" For incapacitated or unconscious pilots (Type 3 SD), an odor similar to smelling salts could help the pilot regain consciousness and control.

Post-Flight Analyses

All the old and new technologies to combat SD incidents have uncertain effectiveness, unless a thorough data gathering and analysis effort is begun. The goal should be to better understand and characterize SD events, and to determine the efficacy of the various SD mitigation tools. Only with *post hoc* (post SD event) analyses will researchers have an objective method to assess the most effective SO enhancing, or SD prevention and recovery techniques devised by researchers (Lyons et al., 1993). Also, an operational analysis system provides the feedback and statistics needed to validate laboratory research results. And, data analyses provide an objective foundation for developing and testing human performance models, such as the multisensory models described in the next chapter.

Recent post-flight data analysis efforts in worldwide commercial aviation have paid huge dividends in understanding the impact of changes to such key flight safety components as airplane systems, pilot training, air traffic control procedures, and airport conditions. The US Air Force has recently begun such a flight data monitoring program for its C-17s. The value of regular consistent objective feedback is enormous, as global aviation data analysis and sharing programs attest.[13] An analogous effort for SD research is absolutely vital.

[11] Personal communication with Dr. Kristen Liggett about auto-recovery systems (11/21/02).
[12] C.f., Pilot's Associate, Rotorcraft Pilot's Associate, French Electronic Copilot, German Cockpit Assistant.
[13] Such programs are known as FOQA and MFOQA in the US, and FDM in Europe and Asia. The global aviation data sharing program is GAIN (see www.gainweb.org).

Conclusion

There are many known SD illusions and causes. How to best combat each one is the challenge of attitude awareness and SD research. The best solution is to blend all of the known helpful training, technologies, and techniques, and to tailor each to the particular SD circumstances. Researchers are investigating a wide variety of technologies. Visual components include head-down, head-up, and helmet-mounted displays. Audio components include 3D audio tones and verbal recovery guidance. Tactile components include vibrating vests. Olfactory cues might be useful when the pilot's other senses are overloaded, or when he or she is incapacitated. Training includes classroom lectures, centrifuge demonstrations, and practice flights. Post-flight data analyses "close the loop" in the research approach by providing feedback about which techniques are the most effective.

The anticipated benefits of this research and development are to help pilots maintain spatial orientation in flight, or, when orientation degrades, to recognize and recover from spatially disorienting situations, thus preventing SD's negative consequences. The cost impact of SD on the US military is over $300 million per year, not counting lives lost. US civilian losses are comparable. Devising a layered approach to even incrementally improve the situation has a multi-million dollar per year potential benefit.

IV. Modeling

The goal of modeling attitude awareness, spatial disorientation, and multisensory workload is to provide a framework for assessing or inferring, in real time, the pilot's level of awareness of the current aircraft orientation, and then, based upon this assessment, implementing an appropriate set of interventions to counter any assessed spatial disorientation events, and their consequences.

We first characterize the pilot's internal state of SD, and then discuss the objective measures that are necessary to infer that state from external variables. Lastly, we introduce and explain a multisensory enhancement to Wickens' Multiple Resource Theory (MRT) – something we call "SAVVOY."

Terminology & Formulas

1. **Explicit meaning of attitude awareness**: Accurate knowledge of momentary Attitude (A) relative to the earth's frame of reference (vertical). As discussed in Chapter 1 of this report, the focus on attitude is directed because the failure of *attitude awareness* appears to be responsible for nearly all SD events. Loss of attitude awareness leads to a stall condition, rapid descent, or unwanted turns, both of the latter leading to undesirable trajectories (the latter, in turn **can** lead to geographical disorientation – a separate issue, not modeled here). For purposes of modeling, we define attitude as a vector quantity composed of pitch (P) and bank (B).

2. **Computational expression of the loss of attitude awareness; i.e., spatial disorientation (SD)**: Ideally, we would like to have a bounded expression of SD varying between 0 and 1 (or possibly between –1 and +1; see below). This makes calculations more tractable. For a pilot with perfect attitude awareness, SD = 0, and therefore perceived attitude (**Ap**) = true attitude (**At**).

Given this expression, then, the loss of attitude awareness (onset of SD) can be expressed in two distinct ways, each with different implications:

(1) SD = Var(**Ap**)/90. This implies that the loss of attitude awareness is related to the variance in (uncertainty of) the momentary attitude, scaled by a maximum value of 90 degrees. Thus a pilot who has absolutely no idea of which way is up, would have SD = 1.0 (this assumes that the variance of a rectangular distribution ranging from 0-180 is 90). We abbreviate the first formula as **VAP**. In essence, this is a confidence measure. Pilots in a Type II SD event know that they are disoriented. That is, they are aware that they have little or no confidence in which direction the true vertical is. Having no confidence yields SD = 1 for this formula.

(2) SD = (|**Ap-At**|)/180. This implies that the loss of attitude awareness is a direct measure of how much the perceived attitude departs from the true attitude. It suggests that an illusion has caused a firm belief in an incorrect attitude. Here SD > 0 is a firm belief that something other than vertical is the upright (and SD = 1, for example, is a belief that you are flying right-side up, when you are inverted, or vice versa). We abbreviate formula 2 by **DA** (Difference in Attitude). In contrast with formula 1 (**VAP**), there is no single positive (incorrect) belief associated with SD > 0. So, for example, pilots experiencing the Leans typically believe that they are certain where the true vertical is, but they are wrong. If they feel they are level when in fact they are banked 90 degrees, then SD = 0.5 for this formula.

It seems apparent that **VAP** is associated with Type 2 (recognized) SD, and **DA** is associated with Type 1 SD. That is, if pilots do not know that they are disoriented, they will probably hold a strong belief that something other than the true vertical, is the perceived vertical (large **DA**). Knowledge that they are disoriented however might simply throw the pilots into a state of confusion typified by high **VAP**.

There are two ways of thinking about **DA** > 0. As the formula states, it is directly proportional to the deviation of perceived attitude from true attitude, so that an SD of 0.5 (e.g., pilots assume they are level, when they are banked 90 degrees) is half as bad as an SD of 1.0 (e.g., pilots assume that they are level, when in fact they are inverted). This measure does not then distinguish the degree of certainty in the incorrect attitude. It would seem that a pilot who is certain of a 90-degree offset (**DA** = 0.5), has greater SD than one who believes (but is uncertain) that he or she may be at a 180-degree offset from the true attitude (calculated **DA** = 1.0). This greater uncertainty is reflected in a higher **VAP**. Thus we can combine the two concepts **VAP** and **DA** (Figure 8), such that larger penalties are applied for smaller **VAPs** at larger **DA** (i.e., "strong but wrong" is worse than "weak but wrong").

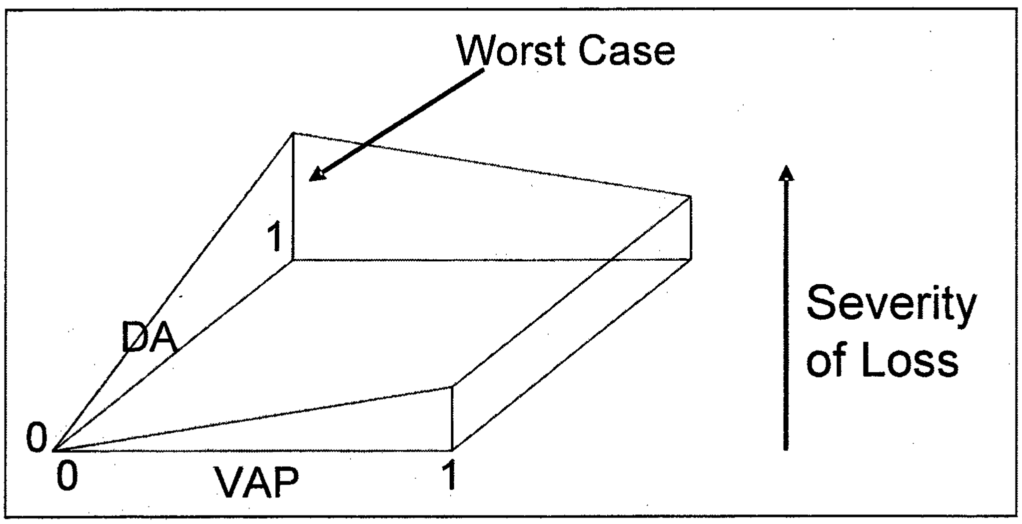

Figure 8. Variance of perceived attitude **(VAP)**, and the difference **(DA)** between perceived attitude **(Ap)** and true attitude **(At)** in relation to the loss of attitude awareness (or onset of SD).

Finally, we recall that A, the vector, is composed of P and B. It may be that Pp and Bp (perceived pitch and bank) are perfectly correlated across all illusions and distortions, but indeed this is probably not the case. For example, the somatogravic illusion in which acceleration leads to perceived pitch up (or deceleration leads to perceived pitch down) certainly affects Pp, but not Bp. The Leans as a precursor to the graveyard spin, effects Bp initially, but not Pp. Hence an open issue is whether to compute a single vector of Attitude, or to break it into its components of P and B. In the latter case, SD scales from 0 to 2.

Our discussion above has focused on the <u>actual</u> state of SD, which exists within the mind of the pilot. An intelligent SD Aiding system will not have direct access to that state, but must infer it on the basis of available, measurable signals, which may be combined computationally. We consider this computation as follows:

3. **Computational basis of SD**: It is feasible to think of SD = 0 (or attitude awareness = 1) as defined by a state in which the pilot, in VMC, is giving full attention to the visual horizon, which always (except at very high altitudes) provides an accurate representation of the vertical. As such, from this state, there are a series of factors that can drive SD upward, some of which have a quantitative basis in prior validating modeling efforts. Among these are:

   3.1 **Reduced quality of visual input**. Use of the attitude indicator (e.g., at night or in IMC), requires focal and foveal vision, which is less effective in providing intuitive *ambient* attitude information (Previc, 1998). As the AI is diminished in size, or more ambiguous about what is represented by the moving element (Roscoe, 1968), the quality of correct attitude information is reduced. As the ambient quality of this information is improved, for example by use of a Malcomb horizon, or background AI (Liggett et al., 1999), the contributions of the AI improve to approach that of the true horizon (SO = 1, SD = 0).

   3.2 **Reduction of attention to true horizon**. There are a variety of computational models that can characterize the loss of precision of spatial estimation associated with attention diversion. Most appropriate may be the optimal control model of Levison and colleagues (1971) that associates an increase in variance of a perceived quantity, as to be inversely proportional to the diversion of attention. As such this can be represented as a contribution of attention diversion to **VAP** (**VAP** = 1 – attn, where "attn" is modeled as the proportion of attention allocated to attitude information; often measured by scanning (Wickens et al., 2003). This formula does not distinguish where attention is diverted to, and could equally describe attention diverted to an auditory channel, as to a visual source in the cockpit (other than the AI). For attention diverted to other visual channels, scanning measures could be used (Wickens et al., 2003). For attention diverted to auditory channels, inferences must be made (e.g., the duration of diversion is related to the length of an auditory communication in the cockpit, to which the pilot responds).

It is also possible to construct the model such that the diversion of attention away from either the true horizon, or the attitude indicator, will not only increase the variance of perceived attitude (**VAP**), but also provide an **opportunity for attentional capture** by the insidious vestibular system, to the extent that the latter provides erroneous cues. This, in turn, would create an opportunity for **DA**. The advantage of this approach is that the misleading signals provided by the vestibular system can be directly calculated (and therefore are amenable to computational modeling), given the known properties of the otoliths and semi-circular canals to provide false information during periods of sustained accelerations. The amount of such signals can range from slight (e.g., the Leans, in a sustained turn) to large (Coriolis). Finally while some other channels of information may degrade attitude awareness by distraction, other artificial channels can restore attitude awareness, even if they direct attention away from the valid horizon sources of correct attitude information. Such artificial channels, as we have previously noted, would include auditory stimulation, voice commands, and tactile sensors.

In summary:

- Attitude awareness can be modeled with a "gold standard" of **Ap** = **At** in VMC.

- Degradation from this state (that is, SD) can be modeled by reduced quality attitude information within the cockpit, diversion of attention **away** from attitude sources, and direction of attention **toward** the vestibular system at times of accelerated flight.
- Attention away is captured by the measure **VAP** and there are quantitative models existing to describe this.
- The cost of attention directed toward the vestibular inputs can be calculated by physical formula related to the effects of sustained acceleration on the otoliths and semi-circular canals, which yield misleading signals. The latter constitutes a separate, independent module of the computational model, and can be used to predict **DA**.

Simulation experiments in Phase II will be designed to assess the extent to which the degree of SD actually experienced by pilots will correlate with the predicted variables described above.

A final property of any computational model to be used in implementing countermeasures is the model's own assessment of self-confidence in its assessment of SD state. One can envision two scenarios, both with the same assessment of SD level (e.g., **VAP** = 0.9), but one assessment reached on the basis of a number of very reliable information channels, and the other reached on the basis of a small number of unreliable sources. An intelligent system should be considerably more cautious in intervening aggressively (e.g., taking control of the aircraft) in the latter case than in the former. Where possible, our approach provides some measure of the confidence in the SD assessment.

Because attention mismanagement (i.e., distraction) is a key component in many SD mishaps and because it is important to consider in the above formulas (**VAP** and **DA**), we now turn to modeling the pilot's attention in the form of a multisensory workload measure, SAVVOY, that expands upon Wickens' Multiple Resource Theory.

Expanding upon MRT

Wickens' multiple resource theory (MRT) says to use the maximum number of different sensory resources/channels to "get through" any distractions. Since our goal is a multisensory approach to combating SD and since Wickens' MRT focuses on visual and auditory channels, we have expanded MRT to include somatic, vestibular, and olfactory senses. The resulting workload model, which we call SAVVOY (somatic, auditory, visual, vestibular, olfactory, psychomotor-primary, psychomotor-secondary, and cognitive), is useful for helping our SD Aiding System (detailed in Chapter VI) determine which countermeasure(s) to apply under varying conditions. For example, if the pilot is in a high G maneuver, tactile cues are less likely to be detected by the pilot due to "high somatic workload." Similarly, if the pilot is talking on the radio or to a backseater, audio cues may be ineffective due to high audio workload.

During our demonstration scenarios, we model the hypothetical pilot workload in all the SAVVOY channels and use that information to influence the countermeasures presented by our SD Aiding System.

SD Assessment Models

To this point, this chapter has presented the detailed theoretical basis for modeling SD and attitude awareness based on the research in the SD literature. The remainder of this chapter is devoted to the actual SD modeling done for the Phase I demonstration. Two models of SD were developed to detect the occurrence of the Leans and Coriolis illusions – one model for each illusion. Each of the models is based on its description from Chapter II. They each use observable data from the aircraft and pilot to assess the state of the vestibular system relative to the actual attitude of the aircraft.

Model of Leans

The model of the Leans is expressed as a timed sequence of events with the certainty of the assessment of the disorientation increasing with each successive event as shown in Figure 9. The first event is the initiation of a roll at a rate below the vestibular threshold (Mulder's constant of 2°/sec). The second event is a roll angle of greater than 5 degrees that lasts longer than 5 seconds. If these two events occur in sequence, it is possible that the pilot has not noticed the ensuing roll angle and that there is a difference between the pilot's perceived attitude (**Ap**) and the true attitude (**At**) of the aircraft. As such, the model indicates a possibility of SD but only at a very low confidence level. The third event is the loss of altitude as measured by negative vertical velocity. If this event follows the first two, it is possible that the pilot has also not noticed the loss of altitude and the model represents an increased confidence in its assessment of the Leans (shown as increasing certainty of SD in Figure 9). The fourth event is a roll well above the vestibular threshold (i.e., greater than 5°/sec and with sufficient duration) in the opposite direction from that of the first event. If this occurs following the first three events, it is possible that the pilot has now noticed the roll angle and has quickly corrected back toward level. When this occurs, the pilot's vestibular system will register a roll in the opposite direction, again resulting in a difference between the perceived attitude (**Ap**) and the actual attitude (**At**) of the aircraft. At this point the model represents a high level of SD certainty. The final event in the model is the tilt of the pilot's head opposite the perceived roll angle. If this occurs following the other four events, it is likely that the pilot is experiencing the Leans and the model represents an even higher level of SD certainty.

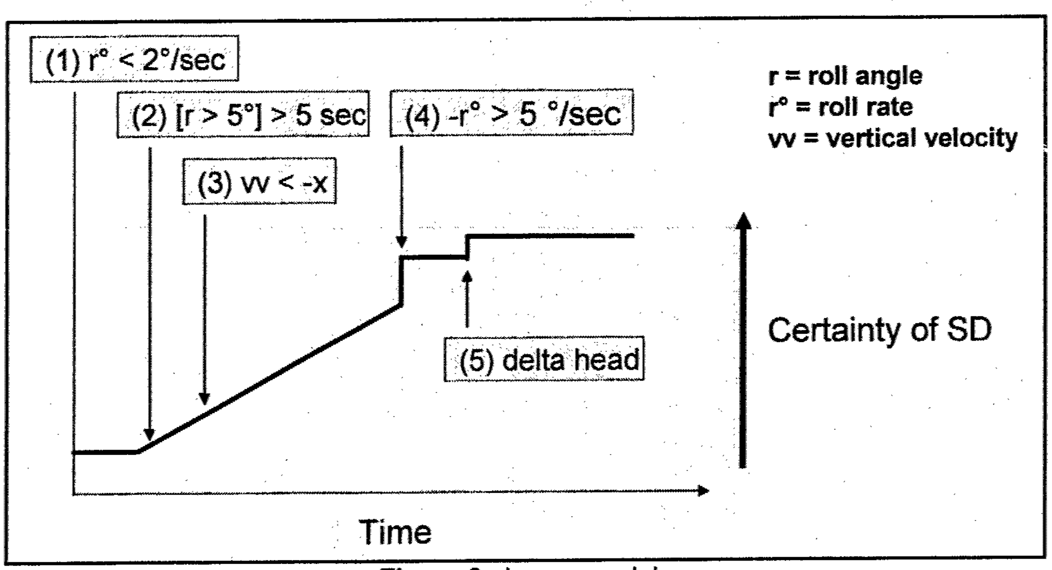

Figure 9. Leans model.

Model of Coriolis

Unlike the Leans, the model of the Coriolis illusion is not expressed as a sequence of events but as an instantaneous occurrence. The model is expressed by the maneuvering of the aircraft relative to the movements of the pilot's head in the three different planes (yaw, pitch and roll). The first event is the aircraft maneuvering such that the rate of change in any of the three planes is above the vestibular threshold (Mulder's constant). If during this maneuvering the pilot's head moves greater than 30 degrees from center in either of the other two planes, then there is the potential for the Coriolis illusion to occur. For example, Coriolis is likely to occur if the aircraft is in an above threshold roll during which the pilot's head moves a large amount (we used 30°) in either the yaw or pitch planes. Since the Coriolis model is based on an instantaneous occurrence, there is no representation of SD certainty or confidence level. Rather, the model simply indicates whether or not Coriolis may be occurring.

Conclusion

"All models are wrong, but some are useful" (Box, 1979).

The most important benefit from modeling is a deeper and more thorough understanding of the problem being modeled. In starting with a theoretical approach, we ensured that we considered all of the relevant aspects of attitude awareness and spatial disorientation. Going from the theoretical, to what we could practically accomplish in Phase I with realistic aircraft and state parameters meant that we could prove the feasibility of our approach while remaining cognizant of enhancements to be made in Phase II.

By modeling the vestibular system and multi-channel workload, we have learned about important interactions and the series of trigger events that precipitate an SD event. In Phase II, we will calibrate our model and test it in realistic scenarios with real pilots in a motion-based simulator. We will also examine work by Borah et al. (1988) to see where we can leverage their techniques within our own modeling approach.

V. SD Scenarios

To demonstrate the efficacy and broad applicability of our modeling and countermeasure approach, we will examine both slow- and rapid-onset SD events. We also want to focus on common and catastrophic events so that we ensure the broad coverage of our solution. The Leans are one of the most common illusions (Holmes et al., 2003), and so it is the focus of our first, slow-onset scenario. The compelling nature of the Coriolis illusion makes it ideal as the focus of our second, rapid-onset scenario.

Scenario #1 (slow onset of SD; the Leans)

On the third day of the war over Iraq, F-22C pilot Captain Luke Keller takes-off with a full load of bombs for tonight's target. It's a moonless night over the desert as Luke climbs to an intermediate altitude of FL200. No need to go higher, since the US-led coalition has air supremacy. Luke is tired from the pace of the war, but excited to be doing real missions instead of practice runs and squadron paperwork back home at Langley. As he levels-off and studies the intelligence photos for his target, the aircraft enters a very slow and shallow left bank. Luke does not notice it for many seconds as his altitude slowly decreases. When he does, he snaps back to his desired heading (which induces the Leans). He feels like he's now in a right bank, and so nudges the stick left. He oscillates back-and-forth with each cycle diverging into greater bank angles. After several seconds, he is in a full-blown unusual attitude and his altitude is rapidly decreasing.

Fortunately for Luke, his F-22C is equipped with the latest SD Aiding System, which detects his situation and applies increasingly intrusive countermeasures. With such assistance, Luke recovers after what seems an eternity, but is only about 60 seconds. He calms down, climbs back to FL200 and proceeds on course, completing his mission as planned.

When he returns to base, he has quite a war story to tell about how his SD Aiding System saved him, his new F-22C (at $40M a copy), and his mission.

Scenario #2 (rapid onset of SD; Coriolis)

This scenario is similar to #1 except that the set-up is a tight turn followed by a flash of light from an explosion behind and to the right of Captain Kristi Oster. She quickly turns her head, drawn to the flash, and experiences a severe Coriolis illusion. Within seconds she is tumbling from the sky as her head spins and her F-15C plummets toward the desert floor. At the last moment, her newly installed SD Aiding System triggers an auto-recovery and saves Captain Oster and her jet.

After several minutes to regain her composure and contact command post, she receives a new mission and proceeds on her way. Upon her return to base, she is met by the squadron flight surgeon who does a follow-up exam to determine if there are any lingering effects from her incident. The crew chief and other maintenance folks also inspect her F-15C for signs of over-stressed wings, panels, pylons, etc.

Demonstration Scenarios

To create the scenarios for our demonstration, we used an off-the-shelf PC flight simulator called X-Plane.[14] It includes a number of different aircraft and a data collection features that output flight data parameters recorded during a simulated flight. Using a simulated F-22, the lead author flew two scenarios representing the Leans and Coriolis illusions (as described in the above scenarios). Table 3 shows a sample of the resulting flight data. The first column shows the elapsed time in seconds and the frequency at which the data are updated (~ 8 hertz). The two scenarios are each about 60 seconds long but the elapsed time shows them starting around 195 seconds as it took that long to takeoff and achieve the desired position within the simulated flight before beginning the desired scenario maneuver sequence. The full data set for these two scenarios includes 600-700 data events. The complete list of flight parameters includes: elapsed time, barometric altitude, heading, pitch, roll, pitch rate, roll rate, indicated air speed, vertical speed indicated, angle of attack, radio altitude, roll rate change, pitch rate change, commanded altitude, and commanded heading.

Table 3. Aircraft scenario parameters.

Elapse time	Baro Alt	Hdg mag	Pitch	Roll	Pitch rate	Roll rate	IAS	VSI	AOA	Radio Alt
sec	feet msl	deg	deg	deg	deg/sec	deg/sec	knots	fpm	units	feet AGL
195.88446	6170	27.8	2.72	0.43			399	32.5	2.80	6165
195.99158	6170	27.8	2.72	0.44	-0.0049	0.0114	399	33.7	2.80	6165
196.09824	6170	27.8	2.72	0.44	-0.0058	0.0100	399	34.8	2.80	6165
196.20444	6170	27.8	2.72	0.44	-0.0040	0.0099	399	35.9	2.80	6165
196.3287	6170	27.8	2.72	0.44	-0.0017	0.0069	399	37.1	2.80	6165
196.43491	6170	27.8	2.72	0.44	0.0099	0.0026	399	38.1	2.80	6165
196.55795	6170	27.8	2.72	0.44	0.0264	-0.0064	399	39.2	2.80	6165
196.68155	6171	27.8	2.73	0.43	0.0347	-0.0577	399	40.3	2.80	6165
196.78781	6171	27.8	2.74	0.42	0.0694	-0.0787	399	41.3	2.81	6166
196.87677	6171	27.8	2.75	0.42	0.1167	-0.0409	398	42.2	2.81	6166
197.00143	6171	27.8	2.77	0.42	0.1594	0.0138	398	43.7	2.83	6166
197.10837	6171	27.8	2.78	0.41	0.1030	-0.0728	398	45.4	2.83	6166
197.21402	6171	27.8	2.79	0.40	0.0751	-0.0818	398	47.6	2.83	6166
197.31985	6171	27.8	2.79	0.40	0.0876	-0.0569	398	50.0	2.84	6166
197.42606	6171	27.8	2.81	0.39	0.1288	-0.0714	398	52.8	2.84	6166
197.55057	6172	27.8	2.83	0.37	0.1745	-0.1438	398	56.5	2.85	6167
197.6749	6172	27.8	2.85	0.37	0.1208	-0.0573	398	60.9	2.86	6167

Figures 10 and 11 are graphs of the pitch and roll changes for the Leans and Coriolis scenarios respectively. The Leans scenario starts with a short period of stable flight followed by the initiating event of a slow shallow roll. After that, the scenario simulates the stereotypical Leans sequence of roll oscillations associated with the confusion between the pilot's vestibular system and the actual aircraft attitude. The end of the scenario simulates a potential recovery from the erratic control induced by the illusion.

The Coriolis scenario begins with a short period of stable flight followed by the initiating event of a high roll rate. This is followed by the potential dramatic changes in roll that could occur from the erratic pilot actions associated with the Coriolis illusion. A real occurrence of Coriolis may also include the dramatic pitch changes associated with the *death spiral*. However, for the purposes of this demonstration, only erratic roll commands were simulated. As with the Leans scenario, the Coriolis scenario ends with a recovery.

[14] For details about X-Plane, see http://www.x-plane.com/.

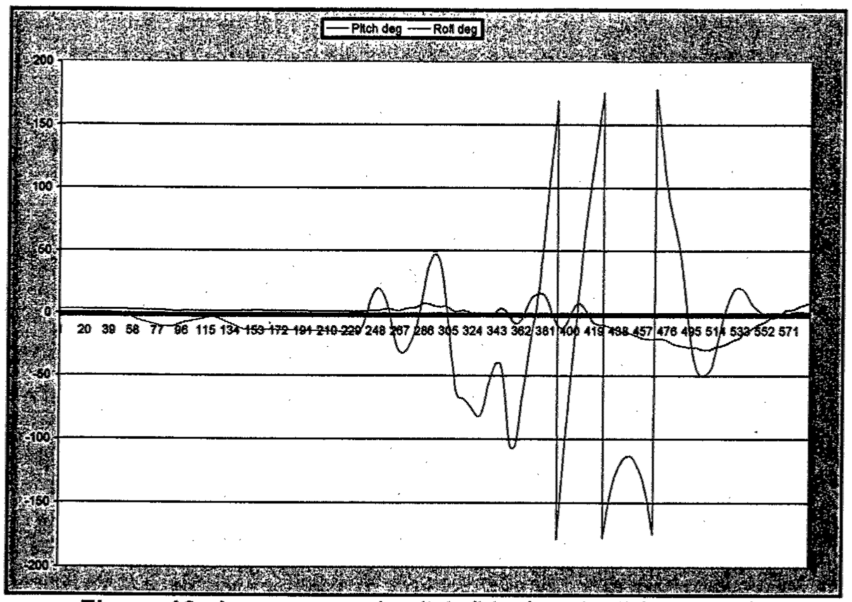

Figure 10. Leans scenario pitch (blue) and roll (magenta).

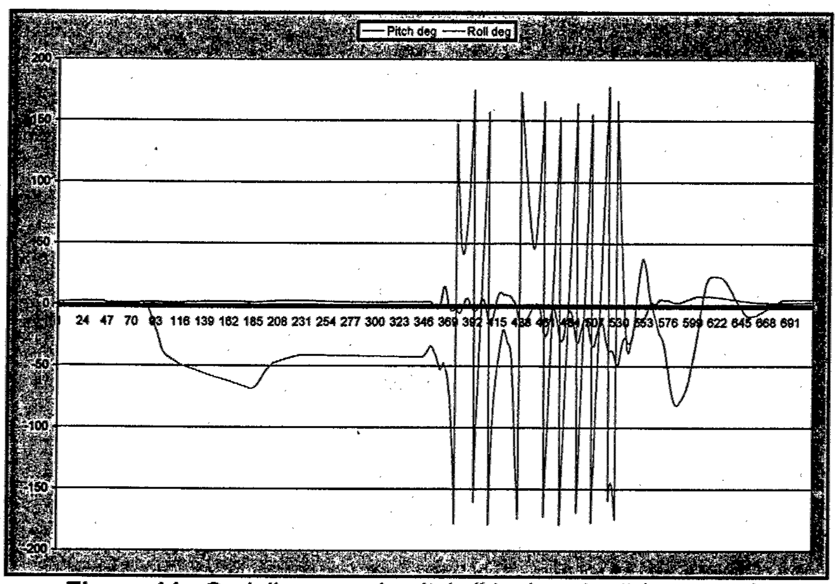

Figure 11. Coriolis scenario pitch (blue) and roll (magenta).

In addition to the aircraft parameters, the scenarios included data specific to the pilot. Since these data were not available from X-plane, they were created manually. The data included pilot head position in three planes (pitch, roll and yaw), and SAVVOY workload scores. The head positions were represented as angles and were added as random numbers. Most of the SAVVOY workload values were also added as random numbers, except where the pilot was experiencing higher G-forces. In these cases, higher values were included for the somatic channel, which inhibited the use of the tactile vest countermeasure.

Conclusion

The importance of effectively combating SD along the whole range of operational exposure is absolutely critical to reducing the human and aircraft costs of this major flying problem and accident causal factor. Clearly, as described in the above scenarios, it is much less expensive to combat SD than to replace pilots and aircraft. The time is ripe to apply prevention and countermeasure strategies to SD via pilot selection, training, mission briefings, intelligent cockpit aiding systems, and rigorous post-event analyses. The above scenarios and our demonstration illustrate the value of a broad approach to combating spatial disorientation.

VI. SD Aiding System Prototype

The overall goal of the SD Aiding System is to achieve a layered approach to solving SD problems. It integrates multisensory displays to help pilots recognize and recover from SD situations. The SD Aiding System prototype demonstrates what could be done in either a simulator or target aircraft to alert pilots of an SD situation, and to help them recover.

The SD Aiding System consists of three components (Figure 12). The first component is the State Table. It contains state data for the pilot, aircraft, and external world, which it uses to analyze the current state of the aircraft, world, and pilot's level of SD (if any). There is also the Countermeasure Assessor, which uses the output from the State Table's assessors to determine the most effective countermeasures for the specific SD situation. Once the countermeasures are decided upon, the appropriate display(s) are activated.

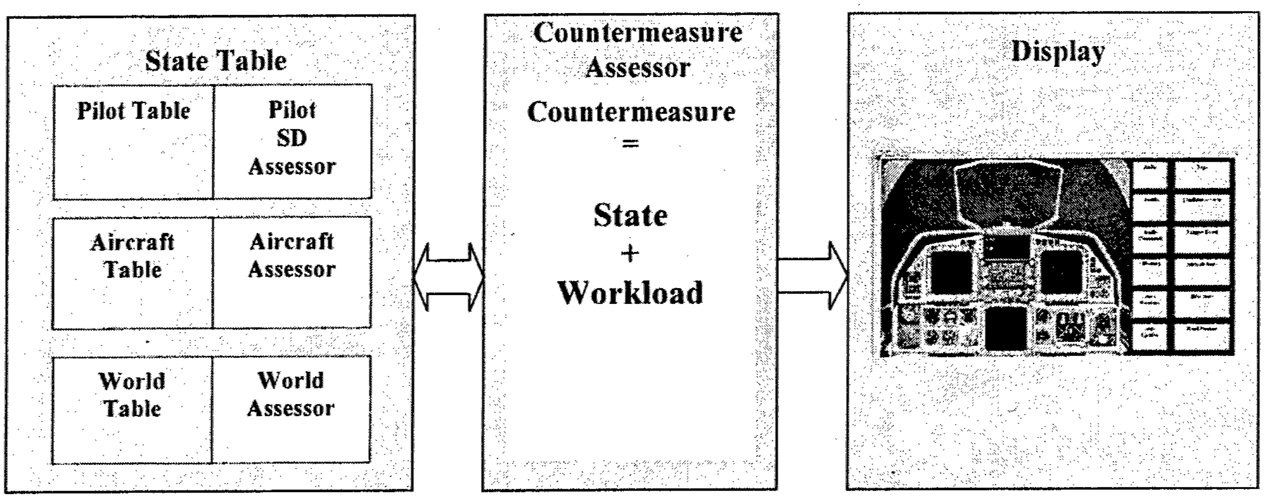

Figure 12. Spatial disorientation aiding system architecture.

As an SD situation evolves, the State Table's assessors continue to assess the state of the pilot, aircraft and world. When the situation changes, it informs the Countermeasure Assessor, so that the compensatory actions can be changed accordingly. Also, as a situation worsens (i.e., its potential consequences become more severe), the processing rate of the system could change accordingly. For example, during a less severe situation, processing might execute at 1 Hz; but, during more severe situations, execution at 8 Hz would be more appropriate.

State Tables

The State Table helps the SD Aiding System create a complete picture of the pilot's current situation and serves as a communication object among the various processes. To create this picture, the system must know something about the aircraft, pilot, and the external factors (i.e., world) that are influencing the pilot's decisions and physiology.

The first piece of this picture is the aircraft for which *raw* data are provided by the aircraft systems (or model, in the case of a simulated aircraft). For instance, the aiding system uses pitch, bank, and airspeed to analyze the motion and position of the plane. These raw data are also used to derive parameters such as pitch rate, roll rate, and change of (delta) airspeed. Both raw and derived data are stored in the State Table; the State Table's assessors and the Countermeasure Assessor use the State Table data (**Table** 4).

Table 4. Aircraft state parameters.

Parameter	Range	Units	Data Type	Comments
Raw Data				
Airspeed	0 to 9999	knots	double	
Altitude	-300 to +60000	feet	double	
AOA	?	?	double	
Heading magnetic	?	degrees	double	
Pitch	-90 to +90	degrees	double	
Pitch command	?	?	double	fore-aft stick position
Radio altitude	-100 to +6000	feet	double	
Roll	-180 to +180	degrees	double	
Roll command	?	?	double	left-right stick position
Vertical speed	-6000 to +6000	feet per minute	double	
Derived Data				
Aircraft state	0, 1, 2, 3, 4, 5, 6, 7, 8, 9			None, SD Inducing, Erratic Control, Suspected Unusual Attitude, Confirmed Unusual Attitude, Impending Crash, Imminent Crash, Recovering, Recovered
Delta airspeed	-100 to +100	knots/second	double	Change of airspeed over time.
Duration of roll	0 to ∞	seconds	double	How long at current roll angle.
Duration of pitch	0 to ∞	seconds	double	How long at current pitch.
Erratic control	0, 1		double	false, true
Ground impact	0-120	seconds	double	Depends on Vertical speed and Radio altitude.
Mulder's Pitch	?	?	double	
Mulder's Pitch Exceed Limit	0, 1		double	false, true
Mulder's Roll	?	?	double	
Mulder's Roll Exceed Limit	?	?	double	
Near flight envelope limit	AOA limits?		double	
Pitch rate	0 to ∞	degrees/second	double	Change of pitch over time.
Pitch rate duration	0 to ∞	seconds	double	How long at the current pitch rate.
Roll rate	? 0 to ∞	degrees/second	double	Change of roll over time.
Roll rate duration	0 to ∞	seconds	double	How long at the current roll rate.
Unusual attitude	0,1,2			no, suspected, confirmed
Vertical accel. duration	0 to ∞	seconds	double	How long at current Gz.

The second piece of the picture is the pilot. The SD Aiding System must assess the current state of the pilot before it can determine the extent to which the pilot is disorientated. The pilot's state also helps determine the best compensatory actions. For instance, it is important for the aiding system to be able to determine whether or not the pilot is incapacitated. To do this, the aiding tool could use existing sensors to measure the pilot's heartbeat rate, skin temperature, pupil dilation and other physiological measures of stress and incapacitation. These pieces of raw physiological data along with the derived data are stored in the Pilot State Table (Table 5).

The last data set needed to finish the picture of the pilot's situation is the state of the external world. These data are important because external events can increase the probability of spatial disorientation, and influence how pilots should attempt to recover from their disorientation. Examples of raw data are the presence of threats, time of day, visibility, and latitude/longitude. These data can be used to determine if the pilot is in combat, whether it is day or night, and the type of terrain over which the pilot is flying (**Table** 6).

Table 5. Pilot state parameters.

Parameter	Range	Units	Data Type	Comments
Raw Data				
Head position pitch	?	?	double	
Head position roll	?	?	double	
Somatic workload	0-7	(like VACP)	double	
Auditory workload	0-7	(like VACP)	double	
Vestibular workload	0-7	(like VACP)	double	
Visual workload	0-7	(like VACP)	double	
Olfactory workload	0-7	(like VACP)	double	
Psychomotor workload	0-7	(like VACP)	double	
Derived Data				
Somatic level	0, 1, 2, 3		double	None, low, medium, high
Auditory level	0, 1, 2, 3		double	None, low, medium, high
Vestibular level	0, 1, 2, 3		double	None, low, medium, high
Visual level	0, 1, 2, 3		double	None, low, medium, high
Olfactory level	0, 1, 2, 3		double	None, low, medium, high
Psychomotor level	0, 1, 2, 3		double	None, low, medium, high

Table 6. External world state parameters.

World Parameter	Range	Units	Data Type	Comments
Raw Data				
Time	0 to ∞		seconds	Scenario duration.
Derived Data				
Combat	0 or 1		binary	Currently, this is set by the model.

Since there is no "horizon visible" sensor on any aircraft of which we are aware, we can use OKCR to give our aiding system an indication of pilot state and orientation with the visible horizon. If the aircraft is banked and the pilot's head position indicates OKCR, then we can assume that the horizon is visible. A lack of OKCR may indicate that there is no visible horizon. In any event, pilot head position is important to our modeling and countermeasures aiding because it is part of the assessment of pilot susceptibility to SD (especially Coriolis).

Micro Saint Model – Aircraft, Pilot, World

For Phase I, a computer model is used in place of a simulator or aircraft to simulate the states of the aircraft and the pilot. The model functions by using the data from the scenarios and supplying that data to the State Table in much the same way that data would be supplied by a flight simulator or actual aircraft. The SD Aiding System then uses the data from the State Table to determine if the pilot is experiencing SD. The aircraft and pilot models are in the latest version of Micro Analysis & Design's discrete event simulation tool called Micro Saint Sharp.

The first step was to convert the scenario data from the spreadsheet format shown in Chapter V (Table 3) to Micro Saint Sharp code. Each row in the spreadsheets represents a data event that details the state of the aircraft and pilot for a specific time period. Each successive data event represents state changes as time advances. An Excel macro was developed to take the data for each event and to transpose it into a two-dimensional data array. The array holds the values for each state variable for each timed event. For example, the code '*ScenarioData[3, 5] = 0.43868;*' is the data from the third timed event and the fifth column in the spreadsheet corresponding to the roll angle. The code representing the full data set for one of the 60-second scenarios is over 9000 lines long. The duration of each event is calculated based on the elapsed time from the first column of the spreadsheet. The data was recorded from X-plane at about 8 Hz, so the duration for each data event is about 1/8 of a second.

The Micro Saint Sharp model is a combination of a flight scenario data in the *ScenarioData* array and a task network diagram. The basic network diagram (Figure 13) is a combination of object nodes and connections. The nodes represent events while the connections represent the basic flow through the network. Each node is associated with a time period that advances the simulation clock and that contains code to change the values of state variables within the model. The first node is simply a placeholder to begin the model. The second node is used to update the state variables from the scenario for each time period. Two different paths lead from this node showing that the network flow can continue back to itself (the small looped arrow on top of node 2) or to the end scenario node. Each time node 2 is executed, it will reference the next data event from the scenario data set, and send that data row to the State Table. This is analogous to receiving flight data from a flight simulator or a real aircraft. This process continues until all the scenario data events have been executed.

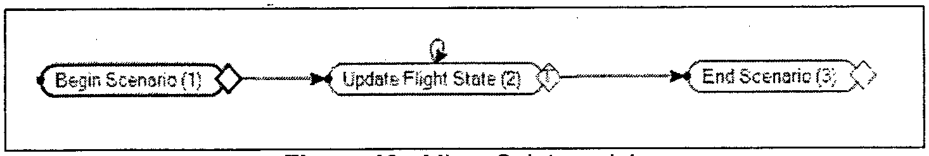

Figure 13. Micro Saint model.

Node 2 also advances the simulation clock by the amount of the duration of the data event. Along with the flight and pilot data, the value of the simulation clock is sent to the State Table, which functions as the SD Aiding System's clock. The State Assessor uses this clock to determine the timed sequence of events for assessing SD (for example, Figure 9 in Chapter IV).

For the Phase I demonstration, the simulation was used in a deterministic mode in which the time periods and state values for each event did not vary across different model executions. This allowed us to repeatedly simulate exactly the same disorientation sequence in order to evaluate the proper execution of the rest of the SD Aiding System. The simulation could also be executed stochastically such that the time and state values would vary randomly within some distribution. This would allow the model to represent variations to the original scenarios to help determine the sensitivity and accuracy of our SD illusion models.

The Micro Saint Sharp model also includes workload score calculations. These workload scores are stored in the State Table and used by the Countermeasure Assessor to determine the potential effectiveness of different compensatory actions in a specific SD situation. We derive our workload assessment from Wickens' Multiple Resource Theory, and add other sensory channels to Wickens' visual, auditory, and psychomotor set. The resulting set, which we call SAVVOY, represents somatic, auditory, visual, vestibular, olfactory, and psychomotor workload scores For psychomotor, we have primary and secondary observable actions. Primary actions are the pilot's flight control actions. Secondary actions are everything else (such as pushing buttons or turning knobs). We also infer cognitive effort to complete the model of pilot workload.

Assessors

Once the State Table is filled, the SD Aiding System uses this information to determine the extent to which the pilot is experiencing spatial disorientation and the best way to help the pilot recover. The assessors, which are part of the State Table, do the first part of this task. They determine the extent to which the pilot is spatially disoriented and the risk surrounding the current situation. These different assessors within the State Table will be referred to as the State Assessor in the rest of this description of the SD Aiding System prototype. The Countermeasure Assessor determines the appropriate compensatory actions, based on the outputs of the State Assessor.

As mentioned earlier, the SD Aiding System's architecture relies upon a newly developed software product, Micro Saint Sharp. This software has two features that the SD Aiding System uses. The first feature was previously introduced in the State Table subsection; it is a *base plug-in interface* that is used for transferring data from the Micro Saint Sharp model to other modules of the SD Aiding System. The second feature is a Micro Saint Sharp *wrapper class* that allows for the rapid prototyping of C# software. The Micro Saint Sharp wrapper supports having all the SD Aiding System components in one piece of software, including the pilot/aircraft model (Figure 14).

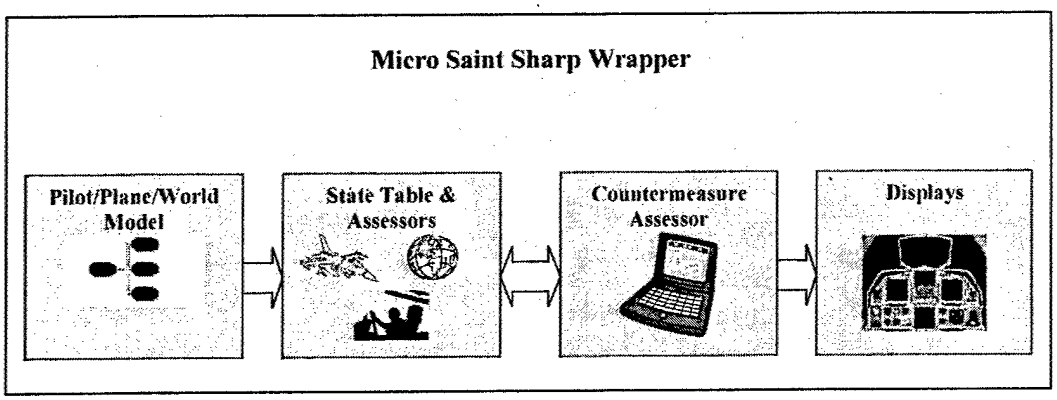

Figure 14. Architecture that uses Micro Saint Sharp for model(s).

State Assessor

The State Assessor's primary task is to detect an SD situation by monitoring the current states of the pilot, aircraft, and world via the data in the State Table. There are three functions that work together to estimate the pilot's spatial disorientation and the severity of the situation (Figure 15): one for the pilot, one for the aircraft, and one for the world.

SD Assessor

The first function is the SD Assessor, which monitors the pilot's vestibular system relative to the aircraft attitude using the SD models of Leans and Coriolis. Its primary goal is to estimate if the pilot has become spatially disoriented, what type of illusion he or she may be experiencing, and the severity of the illusion. This is based on how the pilot's vestibular system reacts to the aircraft's angular accelerations and the pilot's head movements.

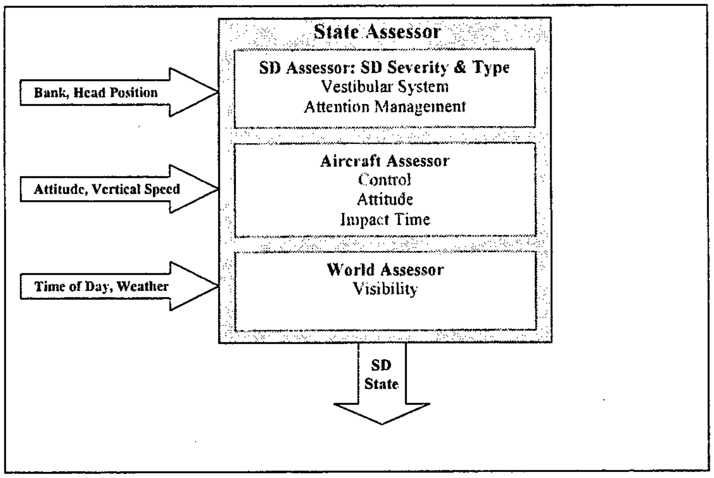

Figure 15. State Assessor.

The SD Assessor is executed each time the State Table is updated with new data about the state of the aircraft or the pilot. For the two demonstration scenarios (Chapter V), this can be as frequently as 8 times per second of simulation time. The Leans and Coriolis models are coded as a series of *if-then* statements and flags used to determine if the progressing state of the aircraft and pilot match the SD trigger events from the models. As described previously, we use the Mulder's constant to determine, for each data event, if the maneuvers of the aircraft have exceeded the vestibular threshold for pitch and roll (we ignore yaw, for now). Both models in the SD assessor use this calculation when evaluating the state of the vestibular system.

Leans Assessor

Since the Leans model is based on a sequence of SD triggering events, the code must keep track of which events have occurred within the sequence. In addition, it must determine if trigger events that have already occurred are still valid. Each time the State Table is updated, the Leans Assessor begins by looking for a roll rate that the vestibular system does not notice based on the rate and duration being below Mulder's constant. For the next State Table update, it first checks that any maneuvers have exceeded Mulder's constant. If Mulder's constant is exceeded (i.e., the motion is detected), the Leans Assessor resets the first trigger and starts over again. But, if Mulder's is still not exceeded, the Leans Assessor then looks for a roll angle of greater than 5 degrees. As the scenario continues, if the pilot's vestibular system is still not reacting based on the Mulder's calculation and the roll angle stays at greater than 5 degrees for greater than 5 seconds, the assessor will determine that a Leans SD has begun and will tell the rest of the system that a Leans is occurring with a low level of confidence. If these conditions continue, the assessor will check to see if the aircraft is losing altitude. If it is, then the assessor will increase the confidence level to medium. If these conditions continue, the assessor will look for a roll rate above the threshold of the vestibular system based on the Mulder's calculation. If this occurs, the assessor will increase the SD confidence level to high. Finally, if all these conditions have occurred in sequence and the pilot's head position deviates in the opposite direction from the roll back, the SD confidence level is increased to very high.

The second SD trigger event requires that a roll of greater than 5 degrees be held for greater than 5 seconds. During the evaluation of the demonstration scenario, it is quite common for the 5-degree roll event to begin but not last the required 5 seconds before reducing to less than 5 degrees. When this occurs, the assessor again determines if the first event was still valid and for the initiation of the second event. In this manner, the Leans Assessor keeps constant track of the state of the aircraft and pilot relative to the Leans model event sequence.

Coriolis Assessor

The coding for the Coriolis Assessor is simpler than the Leans because the Coriolis Model requires only a simultaneous combination of two events. Each time the State Table is updated, the assessor checks to see if the Mulder's constant has been exceeded in any of the three planes (yaw, pitch or roll) and if the pilot's head is turned greater than 30 degrees in either of the other two planes. (In the current prototype, we ignored yaw due to the lack of yaw data.) If these two events occur simultaneously, the Coriolis Assessor determines that an SD may be occurring and sets the confidence level at medium. For example, if the aircraft is changing pitch fast enough to exceed the Mulder's constant for pitch and the pilot's head is turned greater than 30 degrees in the roll plane, the assessor would determine that the pilot could begin to encounter the effects of the Coriolis Illusion. Unlike the Leans Assessor, the Coriolis Assessor does not keep track of any previous events or check if other events are occurring.

Table 7 summarizes the previous two paragraphs.

Table 7. State Assessor outputs.

Parameter	Range	Units	Data Type	Comments
Confidence level	0, 1, 2, 3			None, Low, Moderate, High
Illusion type	0, 1, 2			None, Leans, Coriolis
Trigger event	0, 1, 2, 3, 4, 5, 6, 7, 8, 9			None, Sub-threshold Roll Rate, Roll Greater than 5 degrees, Loss of Altitude, Sudden Reverse Correction, Reverse Neck Rotation, Head Roll or Yaw, Head Pitch or Yaw, Head Roll or Pitch

When an SD event has been detected, the system must determine the severity of the pilot's situation (Figure 16). The importance of SD severity can be seen in the SD remediation network. This network implies that an increasing severity of SD warrants an increasing level of aiding. This is where the other components of the State Assessor become important.

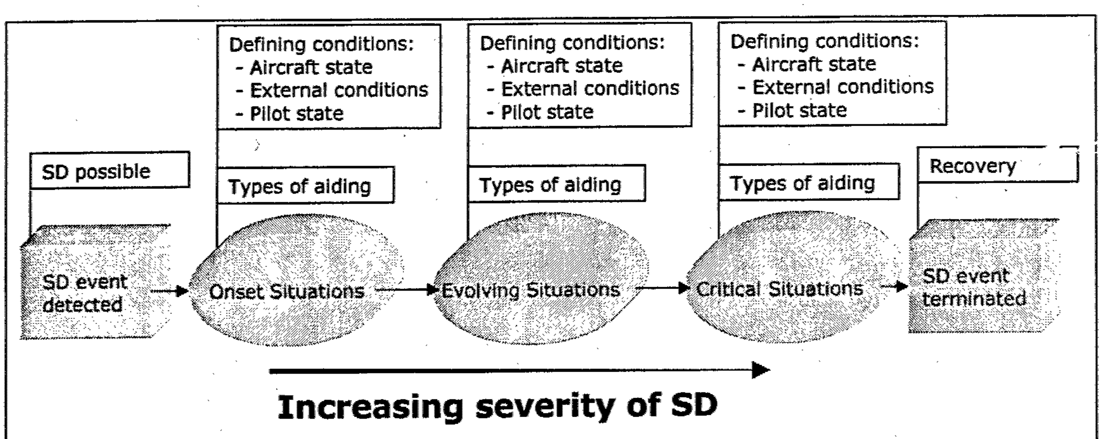

Figure 16. SD remediation network.

Aircraft Assessor & World Assessor

The Aircraft and World Assessors help the State Assessor estimate the severity of the pilot's situation by analyzing aircraft and world state data. SD events can be divided into three primary levels of severity, where each level infers the goal of the SD Aiding System. These levels are:

- Onset situations: Emphasis on prevention (Figure 17)
- Evolving situations: Emphasis on helping pilot recognize and recover (Figure 18)
- Critical situations: Emphasis on recovery (Figure 19)

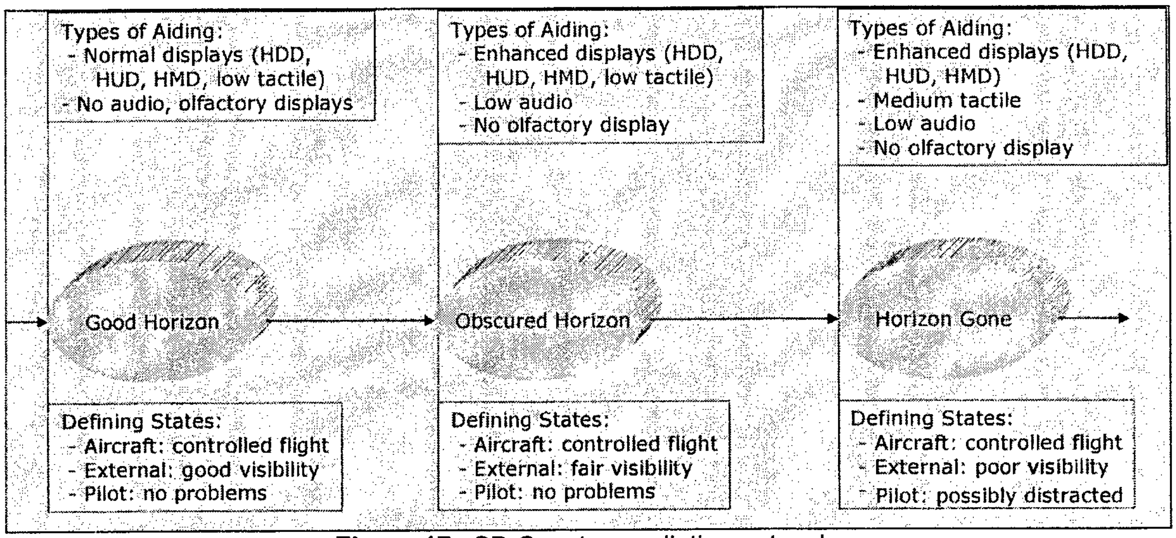

Figure 17. SD Onset remediation network.

The State Assessor monitors for situations that fit into the second and third levels, Evolving (Figure18) and Critical situations (Figure 19).

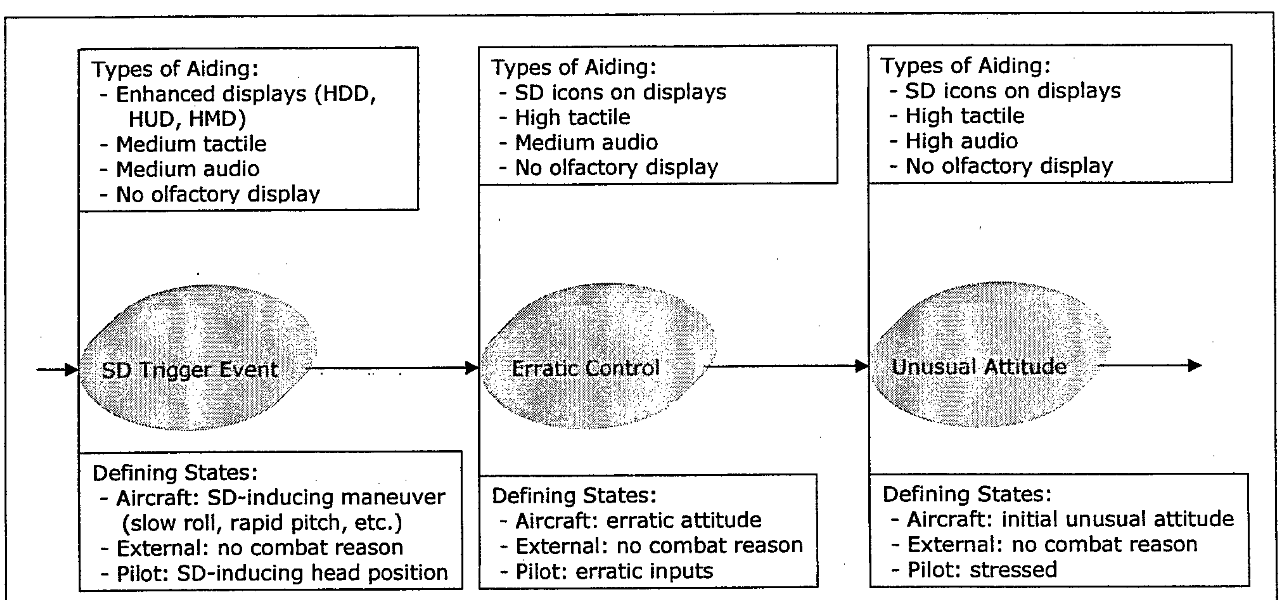

Figure 18. SD Evolving remediation network.

The Aircraft Assessor monitors the aircraft's state. Its primary goal is to estimate the situation's current risk based on the aircraft's acceleration and position. For instance, the pilot is in a more severe situation if the aircraft is in an unusual attitude and about to crash (Figure 19), and this assessor monitors the aircraft's time until impact with the terrain. The less time the pilot has to recognize and recover from SD, the more intrusive the countermeasures must be.

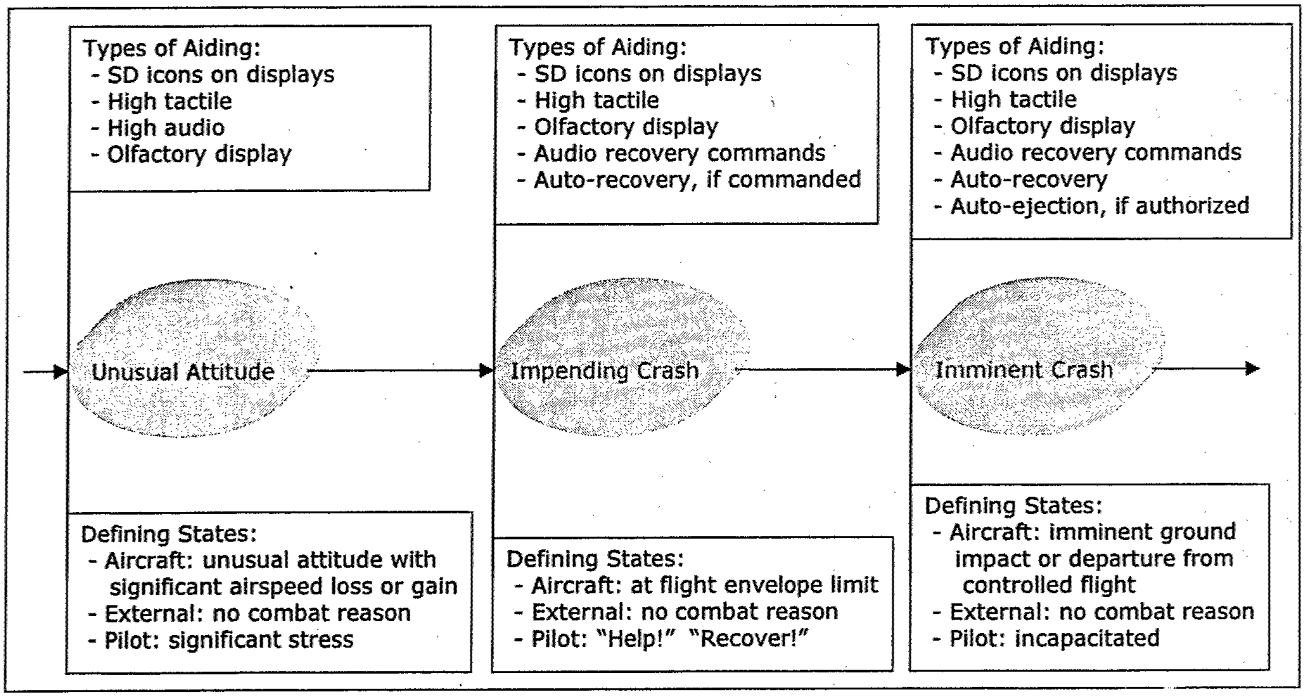

Figure 19. SD Critical remediation network.

The World Assessor monitors the external world's state. In particular, it is concerned with factors that contribute to or increase the pilot's vulnerability to SD. These factors include visibility (is the horizon visible?), and the presence of enemy threats. One example is that pilots are more susceptible to SD if they cannot see the real horizon. Another example is that we may suspend countermeasure actions if the pilot is jinking to avoid an enemy missile.

These types of calculations are difficult to do, because the required parameters are hard to measure with the technology that is currently available in an aircraft. We do not perform calculations in the prototype that we are not able to do with data provided by a real simulator or aircraft. Consequently, the analyses that occur in this portion of State Assessor are conservative. These concepts are included in our design to ensure completeness.

Countermeasure Assessor

The Countermeasure Assessor uses the SD type and level from the State Assessor to determine what type of cues are appropriate countermeasures. It also uses workload levels (i.e., SAVVOY scores) from the State Table to determine the predicted effectiveness of each countermeasure.

Once the Countermeasure Assessor has selected appropriate countermeasures for the SD situation, it sends this information to the (simulated) aircraft displays. It also stores which countermeasures it is using in the State Table, so that the State Assessor knows which pilot resources are being loaded. The following table contains the type of countermeasures the assessor could select to help the pilot recover from an SD event.

Table 8. Countermeasure Assessor outputs.

Aid Outputs				
Parameter	**Range**	**Units**	**Data Type**	**Comments**
Display status	normal, enhanced			
SD icon	0 or 1			displayed or not
Audio (spatial)	low, medium, high			volume
Audio recovery	0 or 1			active or not
Tactile	low, medium, high			tactor frequency and amplitude
Olfactory	0 or 1			active or not
Auto-recovery	0 or 1			active or not
Auto-ejection	0 or 1			active or not

If the State Assessor detects a change in the current SD event, it alerts the Countermeasure Assessor of this change. For instance, if the State Assessor estimates that the pilot has fully recovered from the SD event, it passes this information to the Countermeasure Assessor. Upon receiving this information, the Countermeasure Assessor terminates the various countermeasures it initiated. The State Assessor also informs the Countermeasure Assessor when the SD situation has either decreased or increased in severity, so that the countermeasures can be changed accordingly.

Countermeasures

The prototype's Countermeasures represent technologies currently available in a cockpit, such as helmet-mounted displays (HMDs), as well as new technologies, such as tactile vests. The Countermeasures are represented in a simplified cockpit image (**Figure** 20) for proof-of-concept demonstration purposes.

SD Aiding System: Class Architecture

SDApplication:

This is a class that inherits from the Micro Saint Sharp wrapper form class. Micro Saint Sharp models can be opened and executed in it. This class/form functions as an executive that opens and executes all the components of the SD Aiding System via a graphical interface. This includes opening the Micro Saint Sharp model of the pilot, airplane, and world.

StateStoragePlugin:

This is a class that inherits from *IPlugin* interface. This is used by the Micro Saint Sharp model to set members of the *StateTable* class.

StateTable:

This class provides access to the raw and derived data for the pilot, aircraft, and world. It has public instances of the following classes: *PilotTable, AircraftTable, WorldTable,* and *CountermeasureTable*. It is accessible by the Micro Saint Sharp model (via *StateStoragePlugin*) and the *CountermeasureAssessor* class. The methods used to determine if a pilot is spatially disorientated, *AssessSDLeans* and *AssessSDCoriolis,* are part of this class. When an assessor determines that the pilot's SD state has changed (i.e., the pilot has become spatially disoriented, or SD has decreased or increased, or the pilot is no longer spatially disoriented), it triggers an event that is monitored by the *CountermeasureAssessor* class. For each triggered event, the *CountermeasureAssessor* determines the appropriate countermeasures to apply based upon the logic illustrated in Figures 17-19.

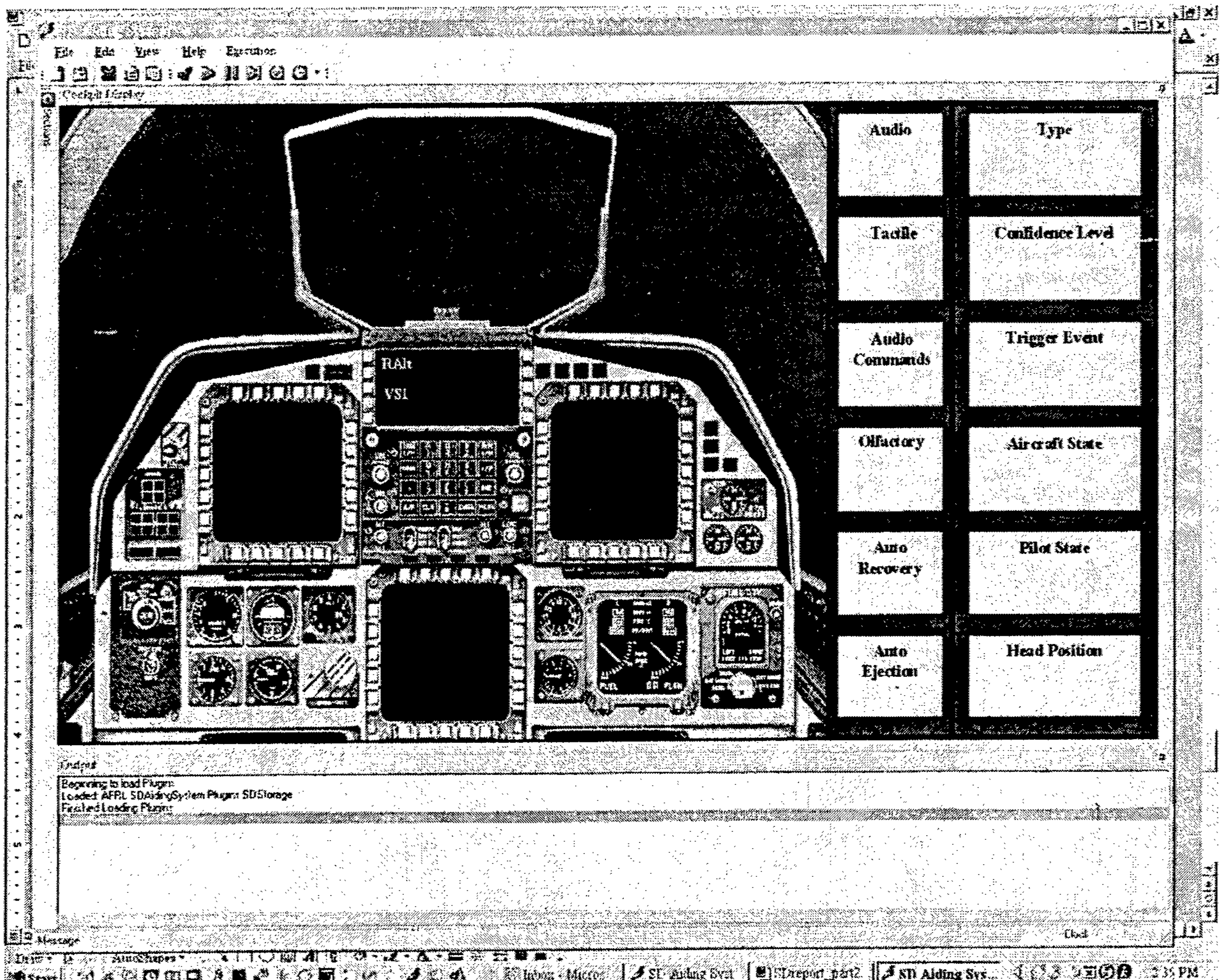

Figure 20. Demonstration screen (F-15E front cockpit) with output 'buttons' for multisensory channels (left column) and assessor outputs (right column).

PilotTable:
This class contains the raw data, data calculations, and derived data for the pilot, plus pilot state assessor functions, which assess the pilot's workload level (SAVVOY scores) and current head position.

AircraftTable:
This class contains the raw data, data calculations, and derived data for the aircraft, plus an aircraft state assessor function, which assesses the aircraft's state (i.e. erratic control, unusual attitude, etc.).

WorldTable:
This class contains the raw data, data calculations, and derived data for the world, plus a world state assessor function, which assesses the world's state (i.e. visibility level, combat, etc.)

CountermeasureAssessor:
This class determines the best countermeasures to apply based on input from an instance of the *StateTable* class. It also uses pilot workload data (SAVVOY scores) from *StateTable* to determine which countermeasures might not be detected due to overload in a particular channel or channels. For example, if the pilot is talking on the radio, then audio cues might be less effective than other sensory cues (e.g., visual, tactile).

CountermeasureDisplays:
This class uses the outputs of the *CountermeasureAssessor* to make the appropriate changes to the SD Aiding System prototype's displays (the column of square buttons in Figure 20).

Conclusion

Our SD Aiding System builds upon prior intelligent cockpit systems, so we have confidence that the design is robust and suitable for a range of applications, including, obviously, spatial disorientation. Our demonstration, which includes the two scenarios described in Chapter V plus a scenario based upon actual data obtained from the Air Force Safety Center proves the feasibility of our model-based concept and approach. The demonstration has been cleared for public release and is available on CD. Interested readers should contact the primary author for a copy of the demonstration, which executes on Windows NT, 2000, and XP, and requires no other software to run.

VII. Major Phase I Accomplishments

For this Phase I SBIR, MA&D accomplished the following major objectives:

- We performed a literature search, including Russian literature, which formed the foundation of our quantitative, model-based approach. An annotated bibliography is Chapter IX, and is hopefully useful to other spatial orientation and disorientation researchers.
- We designed and developed models for the Leans and Coriolis illusions. The Leans model worked with the actual F-16 data we received from the Air Force Safety Center (AFSC) within the last weeks of this project's technical work. We are especially delighted that our SD Aiding system is robust enough to work with this data set in a sensible, realistic manner. (For the actual SD flight data, given to us by AFSC, we took the raw data parameters that we needed, and added small random numbers for other parameters not found in that data set. Then, we ran the data through our SD Aiding System looking for a Leans-like event. We did not try our Coriolis model on the actual data because we did not have pilot head position data. Even without head position data, our Leans model worked because the 5th step (Figure 9), a head tilt, only increases our confidence level; it is not required for a Leans assessment.)
- We enhanced Wickens' (1984) Multiple Resource Theory to account for the other senses critical to this effort. We called the resulting "theory" SAVVOY in honor of Dr. Wickens' location in Savoy, Illinois (at the University of Illinois' Aviation Research Laboratory). The newly included senses are somatic, vestibular, and olfactory. A model of pilot workload, using hypothetical (but realistic) SAVVOY scores, influenced the SD countermeasures applied by our SD Aiding System.
- We invented an SD icon (Figure 7) to be an intuitive representation of the aircraft pitch and roll. How intuitive it actually is remains to be seen via testing in Phase II.
- Most importantly, we delivered a working SD Aiding prototype that serves as an excellent foundation for Phase II development and testing with pilots in a motion-based simulator.

VIII. Phase II Directions

Based upon our success in Phase I, we intend to pursue two major thrusts in Phase II:

1. Enhance and validate our SD illusion models
2. Enhance and evaluate our SD Aiding System

Each of these thrusts has several major components.

Model Improvements

To enhance our SD illusion models, we will:

- Change from a fixed Mulder's constant comparison with acceleration duration, to a more accurate threshold for each of the three axes (pitch, roll, and yaw). Those thresholds are 3.2°/sec for roll, 2.6°/sec for pitch, and 1.1°/sec for yaw. Also, utricle sensing of linear accelerations is discussed (Stapleford, 1968).
- Use more accurate washout values for pitch, roll, and yaw based upon the latest research by Dr. Brian Self and colleagues at USAFA (ongoing experiments).
- More thoroughly test our models with actual de-identified flight data from AFSC, if such data sets are made available to us. If we receive multiple data sets from AFSC, we will use half for development purposes, and the other half for testing. Lessons learned from such testing will be used to make our models more robust.
- Vary our model runs stochastically to explore boundary conditions, stability, and accuracy within a wider range of test conditions than can be done with non-varying X-Plane or AFSC data sets.
- Add models for other illusions – such as somatogravic, Giant Hand, and others – in consultation with our customer. The decision criteria for adding illusions will be based upon the illusions frequency of occurrence for USAF (or other DoD) pilots, and the illusion's dissimilarity to others in our set, so as to cover as much of the "illusion space" as practical. If actual AFSC data suggests an illusion, we will use that fact as another criterion.

To validate our models, we will proceed as follows. The key to our model validation is the creation of a disorienting vestibular illusion, in the GAT-II simulator, as represented in the box in the left center of Figure 21. Our intention for initial model validation is to create the Leans, as this is both common and a precursor to more serious incidents of SD (e.g., Graveyard spin and spiral). Inputs to the illusion creation box are three factors:

(1) Scenario parameters, which are those aspects of the simulation dynamics that are effective in creating the illusion. These include three aspects of bank (primarily, although we might consider pitch or yaw): (i) the degree of bank that is achieved following straight and level flight, (ii) the velocity by which this bank is achieved (rate of change of bank), and (iii) the time duration during which the bank is changing (duration of aircraft rotation). Note that these three parameters are not independent of each other. If a given target bank angle is to be achieved following an X second duration of change, this will dictate the rate of bank. These three parameters can be combined into what we describe as a "bank profile". An additional scenario parameter, which has two states, is whether the bank change is accomplished actively by commands given to the pilot, or passively by the simulation. We intend to vary these scenario parameters across a series of SD trials, in order to assess which combinations produce which levels of SD.

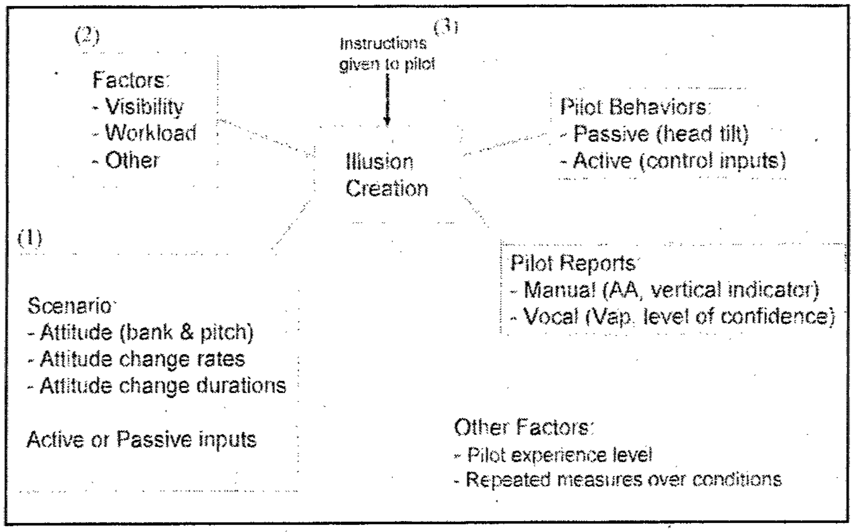

Figure 21. Phase II model validation experimental considerations.

(2) Modulating factors are a set of environmental or operating conditions, which we believe will influence the onset and severity of SD. These include: (i) outside world (true horizon) visibility, which, ideally, will be varied at three levels – perfect, degraded (haze), and absent. We do not anticipate that perfect visibility will produce SD, but it will provide us with a set of "control condition" measures of SD = 0, which our model discriminates from the SD > 0 measures; (ii) mental workload which itself will be discriminated between the amount of workload (extraneous task demands) and the source of workload (visual versus non-visual distractions). There may be other modulating factors we wish to examine, but we believe these two are the most important.

(3) Pilot instructions, such as "Maintain heading 050 at 15,000 feet and 300 knots." Precisely how the instructions will be phrased will be dictated by the measurements we will take (see below).

Assuming that we can design a scenario that can both produce the Leans and vary the magnitude of its experience, via the parameters described above, we must then **assess** the pilot state, as shown as outputs of the illusion creation box in Figure 21. These assessments are reflected both in pilot behavior and explicit pilot reports of SD. **Pilot behavior** includes passive measures – in particular head tilt, which will give us a measure of the pilot's perceived vertical (as inferred by the difference between the perpendicular to the perceived horizon in IMC and the true horizon in VMC). In later simulations another important passive behavioral measure could include measures of eye scanning (away from the horizon). It is possible that we can also obtain passive measures of head rotation, to infer scanning away from the outside world and the attitude indicator. Pilot behavior also includes active measures of flight control inputs (i.e., stick or yoke deflection). These are particularly important, as they will assess the moment of active correction from an undesirable bank.

Pilot reports are the key assessments of the SD state against which our model will be validated. Manual reports will involve periodic assessments of the pilot's belief in the direction of vertical. These can be provided by a "sky pointer" held in the left hand, which can be rapidly oriented toward the pilot's belief of which direction is up. This will provide an objective, quantifiable measure of **DA**. The orientation can be videotaped or assessed by other sensors. Verbal reports will be obtained by asking the pilot to periodically rate his or her degree of certainty in spatial orientation along a 10-point scale. These ratings might be solicited at the same time as the **DA** arrow task. They will provide an estimate of **VAP**.

The experimental design will involve manipulating the input variables on the left of Figure 21 to create several conditions. It remains unclear the extent to which a single pilot will experience all conditions. It is likely that some of the experimental variables (such as ambient workload) will be varied between pilots. Also unclear is the amount of experience that we will need from subject pilots. These uncertainties will be defined as we work with the simulator early in Phase II to develop credible scenarios and appropriate ways of measuring **DA** and **VAP**.

SD Aiding System Improvements

To enhance our SD Aiding System, improvements will include the following.

- Enhance and calibrate our SAVVOY scores to more accurately assess pilot workload in all of the sensory channels in which we are interested.
- We have heard anecdotally that humans habituate to audio or tactile cues within 10-20 seconds. We will search the literature for this claim. If verified, we will constrain our intelligent audio and tactile cuing to account for this habituation.

To evaluate our SD Aiding System, our steps will include the following.

- Test it with as much actual data as practical.
- Perform stochastic testing to check boundary conditions.
- Conduct pilot-in-the-loop (PITL) trials with components of the system, as well as with the complete system.
  - To conduct PITL, we will need approval from USAFA's IRB.
  - To test our multisensory countermeasures, we will first test them in isolation (or use the literature to establish a sensory countermeasure's efficacy), and then test them in combination with others in order to achieve an intelligent multisensory approach that appears to be the best combination for a given situation.

Conclusion

Phase II will give us an opportunity to calibrate and validate our models and to test our SD Aiding System under realistic simulated scenarios with Air Force pilots.

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"Two experiments conducted in a high-fidelity flight simulator examined the effects of guidance symbology, display size, and field of view (FOV) on flight performance and situation awareness within a Synthetic Vision System (SVS). In Experiment 1, 18 pilots flew highlighted and lowlighted tunnel-in-the-sky displays and a less-cluttered follow-me-aircraft (FMA) through a series of curved approaches over rugged terrain. The results revealed that both tunnels supported better flightpath tracking than the FMA due to the availability of more preview information. Increasing tunnel intensity had no benefit on tracking, and in fact, traffic awareness was degraded. In Experiment 2, 24 pilots flew a lowlighted tunnel display configured according to different display sizes (small or large) and FOVs (30° or 60°). Measures of flightpath tracking and terrain awareness generally favored the smaller display and the 60° FOV."

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A superb chapter for human factors engineers that covers human perception, workload, and the context for human performance. "…[C]ontext is a key concept in understanding human behavior." Sensory sensitivity depends on environmental factors, so that "it is difficult to make numerical predictions about sensory performance in particular circumstances, without testing directly." Very salient signals can be useful as warnings, or be distracting nuisances. An iconic "display supports detection, but not discrimination or naming."

"It is in combining three or more movements that it is easy to get into difficulties with compatibility. One classic example is the aircraft attitude indicator…. In the design of the indicator, four movements are involved: of the external world, of the display, of the

control, and of the pilot's turning receptors.... The attitude instrument can show a moving aircraft, in which case the display movement is the same as the...control movement but opposite to the movement of the external world. Or the instrument can show a moving horizon, which is compatible with the view of the external world but not with the movement of the [control]. There is no solution in which all three movements are the same, so some performance errors or delays are inevitable."

Cognitive processing involves: "deciding between alternative interpretations of the evidence; integrating data from all sensory sources, together with knowledge about the possibilities, into an inferred percept that makes best sense of all the information; and, recoding, that is, transforming from one type of code to another." Figure 6.22 on page 131 illustrates the cognitive processing. Figure 6.24 on page 133 shows cognition in relation to the external environment. "A person takes anticipatory action, not to correct the present situation, but to ensure that predicted unacceptable states or events do not occur." "Ideally, the display should make explicit the points that are important for a particular purpose, and provide a framework for thinking." For physical movement skills, "use kinesthetic rather than visual feedback."

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"SD has long been a major aero-medical factor contributing to naval aviation mishaps. In the past, it has been viewed as a generalized phenomenon, described by its vertigo-related symptoms. More recently, however, three distinct types of SD have been identified, each based on whether the aviator recognizes and responds to its onset. In the current retrospective study, Flight Surgeon and Mishap Investigation Report narratives from 33 Class A mishaps occurring from 1980 through 1989 were reviewed. SD was determined to have been a causal factor in all cases. The mishaps were examined to categorize SD into the three descriptive types and to describe the relationship (if any) between SD and various mission-related factors. Aircraft type, phase of flight, time of day, pilot experience, and flight topography were all considered. The results indicate that Types I and II SD could be identified as causal factors in all 33 Class A mishaps. Further, most Type I SD was experienced primarily by helicopter pilots at night while most Type II SD incidents affected jet pilots during day missions."

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"The optokinetic cervico reflex (OKCR) is a recently hypothesized, visually driven reflex that serves to stabilize the image of the external horizon on the retina during roll maneuvers in high-performance aircraft. Although reported anecdotally, head tilt during helicopter flight has not been studied formally. Such research is required to determine the full impact and significance that it may have on the flying performance of a rotary-wing aviator. The aim of this study was to investigate the relationship between horizon position and the perception of orientation and, thus, to generate vital information to assess whether OKCR plays an important role in spatial disorientation. A UH-60 flight simulator study, with 20 volunteer pilots participating, was performed to examine the effects of this reflex during day flight and during flight with night vision goggles (NVGs). The results confirm that the OKCR occurs during simulated helicopter flight, both with and without NVGs. As with previous studies, head roll increased during flight under visual meteorological conditions in relation to an increasing aircraft roll angle up to a maximum sustainable level and then remained constant. Head roll did not occur during flight under instrument meteorological conditions. The presence of the OKCR will impact rotary-wing operations. Various aspects are discussed, and recommendations are made for future research."

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Describes a procedure for non-instrument pilots to fly out of IMC, if they accidentally fly into it.

Carretta, T.R, Perry, D.C., Jr., & Ree, M.J. (1996). Prediction of situational awareness in F-15 pilots. *International Journal of Aviation Psychology, 6*(1), 21-41.

"Situational awareness (SA) is a skill often deemed essential to pilot performance in both combat and non-combat flying. A study was conducted to determine if SA in U.S. Air Force F-15 pilots could be predicted. The participants were 171 active duty F-15 A/C pilots who completed a test battery representative of various psychological constructs proposed or demonstrated to be valid for the prediction of performance in a wide variety of military and civilian jobs. These predictors encompassed measures of cognitive ability, psychomotor ability, and personality. Supervisor and peer ratings of SA were collected. Supervisors and peers showed substantial agreement on the SA ratings of the pilots. The first unrotated principle component extracted from the supervisor and peer ratings accounted for 92.5% of the variability of ratings. The unrotated first principle component served as the SA criterion. Flying experience measured in number of F-15 hours was the best predictor of SA. After controlling for the effects of F-15 flying hours,

the measures of general cognitive ability based on working memory, spatial reasoning, and divided attention were found to be predictive of SA. Psychomotor and personality measures were not predictive. With additional F-15 flying hours it is expected that pilots would improve their ratings of SA."

Chelette, T.L. (2001). Measuring the head tilt illusion during sustained acceleration. *Human Systems IAC Gateway, 12*(3), 4-6.

"Magnitude of roll illusion (in degrees) Roll illusion = 0.3397 x arcsin{(G0.25 – 1) x sin [head pitch] x sin [head yaw]} Pitch illusion = 0.1491 x arcsin{(G0.25 – 1) x sin[head pitch] x cos[head yaw]}" "Specifically, an upward head pitch combined with a head yaw into a turn, as is common in formation flying, can result in a sensation of underbank and a pitch-up of the aircraft. Intended corrective action actually overbanks the aircraft with a pitch down, causing loss of altitude. Downward head pitches during turning, as is common during bombing or strafing runs, can cause a sensation of overbanking. Intended corrective action actually underbanks the aircraft, causing altitude gain that could lead to midair collision when in formation flight."

Cheung, R. (2000). *Non-visual spatial orientation mechanisms.* San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/MechanismsStudies /cheung.pdf

Post-rotational decay in Roll (4s) < Pitch (7s) < Yaw (16s), measured from duration of post-rotational decay of the resulting illusory sensation of rotation. There is a greater rate of error development in roll than in pitch and yaw.

Semicircular canal inadequacies: Limited threshold of vestibular perception 0.14, 0.5 and $0.5°/s^2$ for yaw, roll and pitch respectively. Perceived angular velocity is less than the actual angular velocity. Absence of sensation of rotation during constant velocity rotation. Apparent sensation of rotation in the opposite direction during deceleration. Persistent apparent sensation of rotation in the opposite direction, after physical rotation has actually stopped. Greater rate of error development in roll > pitch > yaw.

Cheung, R., & Hofer, K. (2003). Eye tracking, point of gaze, and performance degradation during disorientation. *Aviation, Space, and Environmental Medicine, 74*(1), 11-20.

"The cognitive cockpit concept has been proposed as a potential disorientation countermeasure. It involves monitoring the pilot's physiological, behavioral and subjective responses during disorientation. This data is combined to provide a real time model of pilot state, which is used as a basis for optimizing pilot performance. This study attempts to investigate whether there are consistent behavioral or physiological *markers* that can be monitored during a specific disorientation scenario. An Integrated Physiological Trainer with interactive aircraft controls and an eye-tracking device was employed. Fourteen subjects proficient in maintaining straight-and-level flight and who have acquired the skills in changing attitude participated in the study. They were exposed to a flight profile consisting of straight-and-level flying and change in attitude without exposure to a head roll (control condition) and a profile with exposure to a head roll (experimental conditions) during constant yaw rotation. Flight performance parameters and subjects' eye movements and point of gaze behavior were monitored continuously. Immediately on the return to upright head position, all subjects reported a strong apparent pitch displacement that lasted < or = 20 s and a lesser sensation of lateral movement. Significant differences ($p < 0.01$) were noted on a number of scanning behaviors between the control and the experimental conditions. The appearance of Nystagmus was apparent as indicated by the number of involuntary saccades during disorientation. Flight performance decrement in the experimental conditions was reflected by a significant deviation in maintaining airspeed ($p < 0.01$). It appears that the pitch illusion consistently affects visual scanning behavior and is responsible for the decrement in flight performance observed in the simulator."

Cheung, R., Money K., Wright, H., & Bateman, W. (1995). Spatial disorientation-implicated accidents in Canadian forces, 1982-92. *Aviation, Space, and Environmental Medicine, 66*(6), 579-85.

"In a recent survey of CF18 aircrew human factors, 44% of pilots reported experience with spatial disorientation (SD), of whom 10% had experienced more than 3 episodes. In order to investigate further, we have completed a retrospective study of SD-implicated category A accidents (where an aircraft is destroyed, declared missing, or damaged beyond economic repair) in the Canadian Forces (CF) during 1982-92. An overview of all SD occurrences (including accidents and incidents) across aircraft types is also presented. Information was gathered concerning the genesis and severity of disorientation so that research effort and pilot training could be appropriately implemented. Mishap investigation summaries involving category A accidents where SD was implicated were obtained from the CF Directorate of Flight Safety and reviewed. We also examined in detail the Board of Inquiry Reports of these accidents. The role of disorientation in these accidents was assessed. There were 62 category A accidents between 1982-92 and, in 14, SD had been assigned as a possible cause factor in the accident records. When divided into the categories of Recognized SD (RSD), Unrecognized SD (USD), and Incapacitating SD (ISD), all but two fell into the category of USD (the pilots were unaware of the disorientation). Of the SD accidents, 11 involved a total loss of 24 lives. The majority of the accidents happened during the day, and pilots' cumulative flying experience did not appear to be a significant factor. According to our assessment, there were two episodes of vestibular origin, involving the somatogravic illusion. Three episodes of disorientation occurred over frozen lakes, one over glassy water, and one over ocean."

Cohen, D., Otakeno, S., Previc, F.H., & Ercoline, W.R. (2001). Effect of "inside-out" and "outside-in" attitude displays on off-axis tracking in pilots and nonpilots. *Aviation, Space, and Environmental Medicine, 72*(3), 170-176.

"Pilots employing helmet-mounted displays spend sustained periods of time looking off-axis, necessitating the inclusion of attitude symbology on the helmet to maintain spatial awareness. We examined how fundamentally different attitude references, a moving-horizon ('inside-out') or a moving-aircraft ('outside-in'), affected pilot and nonpilot attitude control when looking on- or off-axis. Both a rear-view and a side-view outside-in perspective were depicted to investigate the effect of control-display compatibility.... Subjects performed a compensatory pitch-roll tracking task either looking on-axis or 90 degrees off-axis using three symbologies: 1) a compressed pitch ladder with horizon line; 2) a 3-D aircraft representation viewed from the rear; and 3) a 3-D aircraft representation viewed from the side. Tracking error in roll and pitch, control bias, and subjective ratings were collected and analyzed.... There was no significant difference in the tracking performance of U.S. Air Force pilots in pitch and roll using the inside-out or outside-in rear-view formats on- and off-axis, although they preferred the inside-out format. Nonpilots tracked significantly better using the outside-in rear-view format, which they also preferred. Both groups tracked poorly using the outside-in side-view format and control-display compatibility had no important effect. Pilots are equally adept using outside-in and inside-out displays. Given that an outside-in display may better reflect a person's inherent frame of reference for orientation (as evidenced by the nonpilots' superior performance with it), the results seem to indicate that pilots, through experience, have adapted to an inside-out frame of reference."

Collins, D.L., & Harrison, G. (1995). Spatial disorientation episodes among F-15C pilots during Operation Desert Storm. *Journal of Vestibular Research, 5*(6), 405-10.

"Spatial Orientation (SO) under flight conditions is the accurate 'integration' of sensory inputs from the dynamic aviation environment that result in safe and effective goal-oriented performance. Insidious sensory mismatches routinely occur during flight, impeding pilot performance. When this sensory dissonance occurs, if not appropriately resolved, it will result in perceived or actual errors in aircraft control that are estimated to cost the Air Force between \$150 and \$200M per annum in aircraft accidents. A scientific survey was created and administered to 96 F-15C combat pilots after their return from Desert Storm. The survey sought to determine where in the flight profile, and under what conditions, spatial disorientation (SD) episodes occurred. The survey consisted of multiple choice and open-ended questions. The analyses of the data revealed that visual transitions from inside to outside the cockpit (or the reciprocal) [e.g., target acquisition] under different conditions of flight were associated with the occurrence of SD episodes. The frequency of SD episodes varied depending on visual transitions (or no visual transitions) and types of flight conditions (for example, night-time and bad weather). This SD survey provided flight information that allowed us to direct research to those areas that were problematic during combat operations."

Cone, S.M., & Hassoun, J.A. (1992). Attitude awareness enhancements for the F-16 head-up display (Final report ASC-TR-92-5017). Wright-Patterson AFB, OH: Aeronautical Systems Center.

The F-16 System Program Office identified a set of HUD enhancements for evaluation: "(1) extended horizon, (2) ghost horizon, (3) articulated nose down pitch bars, (4) removal of the 2:1 pitch scale compression, (5) moving nose down pitch bar tic marks to the inside of the pitch bars, (6) modified bank angle indicator, and (7) modified zenith/nadir symbols." Experimental results for 15 pilots flying simulated unusual attitude recoveries showed faster reaction times and strong preference for modifications 1-5 & 7. Results for the modified bank angle indicator were mixed.

Costello, R.G. (1976). Continuous compensatory audio manual tracking. In *Proceedings of Twelfth Annual Conference on Manual Control* (NASA TM X-73,170). Moffett Field, CA: Ames Research Center, 406-421.

Glider pilots may use an audio variometer for indicating their sink or climb rate so that they can maintain visual scans and not have to look inside at their vertical speed indicator. Increasing tone pitch indicates climbing; descent is noted by the decreasing pitch of the tone. The author speculates that pilots use the tone for coarse assessments of their flight strategy, while using the horizon for fine tuning their path.

Craig, G., Brown, A., Jennings, S., & Cheung, R. (2003). *Flight test of three attitude indicators for unusual attitude recovery.* Presented at Aerospace Medical Association's Annual Meeting, May 4-9, 2003, San Antonio, TX.

Flight test compared a conventional AI, an arc-segmented attitude reference, and a novel asymmetric AI. During unusual attitude recoveries, the asymmetric AI supported quicker recoveries and fewer errors.

Davenport, C. (2000). *Spatial disorientation: The USAF experience, FY1991-FY2000: How much are we willing to pay*? San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Mishap%20Studies/Davenport.pdf

The top 10 contributing factors to SD mishaps are: attention management, judgment/decision-making, mission demands, psychological factors, mental fatigue, visibility, training, behavior, personal/community factors, and instrumentation.

Davenport, C. (2003). Personal communication (email message of 7/9/2003).

Vestibular threshold of greater than 2 degrees per second per second acceleration normally results in a sensed motion. However, if the pilot is task overloaded, even greater accelerations may not be perceived.

DeHart, R.L., & Davis, J.R. (eds.) (2002). Fundamentals of aerospace medicine (3rd ed., ISBN 0-7817-2898-3). New York: Lippincott Williams & Wilkins.

A *must have* reference for any serious SO/SD researcher. Chapter 8, Spatial Orientation, by A.J. Parmet and Kent K. Gillingham, pages 184-244, covers all of the essentials for this topic, including: translational and rotational motion, actions and reactions, visual orientation, vestibular function, perceptions, other senses of motion and position, illusions, the dynamics of spatial orientation and disorientation, other sensory phenomena, situational awareness, and motion sickness.

Important excerpts are: "the actual vestibular perceptual thresholds are 'constant except when they vary'" (page 201), which supports our model-based Monte Carlo approach to modeling the vestibular system. "The leans [is] the most common of all vestibular illusions in flight" (page 221), which supports our first scenario focusing on the Leans.

Dieterich, M., Bucher, S.F., Seelos, K.C., & Brandt, T. (1998). Horizontal or vertical optokinetic stimulation activates visual motion-sensitive ocular motor and vestibular cortex areas with right hemispheric dominance: An fMRI study. *Brain, 121*, 1479-1495.

Duffy, C.J., & Wurtz, R.H. (1995). Responses of monkey MST neurons to optic flow stimuli with shifted centers. *Journal of Neuroscience, 15*(7), 5192-5208.

Endsley, M.R, & Rosiles, S.A. (1995). Auditory localization for spatial orientation. *Journal of Vestibular Research, 5*(6), 473-85.

"The use of 3D auditory technology that provides localization of auditory cues presented through headphones is proposed as a means of providing supplemental information to pilots on the spatial orientation of an aircraft. This technique shows promise for reducing accidents due to spatial disorientation associated with high visual load. A study was conducted using USAF pilots as subjects to determine desirable inverted question mark cue characteristics for accurately localizing auditory cues using this technique. The study examined the use of 9 different cue types at each of 2 frequency levels. It was found that the accuracy of subjects' localization of cues in elevation was greatly enhanced by the use of multidimensional cues that provided redundant elevation information through varying frequencies and distance from the horizon cues in addition to the inherent spatial location information. Trade-offs in azimuth localization accuracy and response time were noted, however. Recommendations are made for further developing and investigating this technique for the aircraft spatial orientation task."

Engineering Acoustics, Inc. (2003). See: http://www.navysbir.brtrc.com/cap/briefingsadmin/ea.asp.

Describes the tactile situation awareness system (TSAS) and claims reduced perceived workload and improved "performance in spatial tasks, especially in the presence of distracting influences."

Ercoline, W.R. (1997). *Introduction to spatial disorientation training*. Found at: www.sam.brooks.af.mil/web/ram/SPATIALD/instrume.html.

Ercoline, W.R. (1998). In *Minutes of the 22nd meeting of the DoD flight symbology working group*. Moffett Field, CA: NASA Ames Research Center.

Ercoline asserts, "Attitude symbology is <u>not</u> needed on HMDs to maintain attitude awareness when looking off-axis to find and track a target during restricted visibility."

Ercoline, W.R. (2000). *The attitude component of the primary flight reference: Where do we go from here?* San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Primary%20Flight%20Displays/ercolineb.pdf.

Ercoline reports a study of 3 different attitude displays for use with an HMD. The so-called grapefruit presentation had the best results in terms of reaction time, error rates and subject preference. Furthermore, the Class A mishap rate due to SD is largely unchanged since the 1970s.

Ercoline, W.R., DeVilbiss, C.A., & Lyons, T.J. (1994a). Trends in USAF spatial disorientation accidents – 1958-1992. In *Proceedings of the SPIE Conference* (A95-12001-01-54 in Orlando, FL). Bellingham, WA: Society of Photo-Optical Instrumentation Engineers, 257-260.

The rate of major aircraft accidents from the period 1958-1971 was 5.36 per 100,000 flying hours; the rate was 2.22 during the period 1972-1992. Even though the accident rate decreased, the rate of SD-related accidents remained about the same: 0.32 and 0.35.

Ercoline, W.R., Freeman, J.E., Gillingham, K.K., & Lyons, T.J. (1994b). Classification problems of US Air Force Spatial Disorientation accidents, 1989-91. *Aviation, Space and Environmental Medicine, 65,* 147-152.

Ercoline, W.R., & Previc, F. (2001). Spatial disorientation, geographic disorientation, loss of situation awareness, and controlled flight into terrain. *Human Systems IAC Gateway, 12*(3), 10-12.

Spatial disorientation related to the loss of situation awareness.

Ercoline, W.R., Self, B.P., & Matthews, R.S. (2002), Effects of three helmet-mounted display symbologies on unusual attitude recognition and recovery, Aviation Space and Environmental Medicine, Nov;73(11):1053-8.

"Helmet-mounted displays (HMDs) allow pilots to view aircraft instrument information while looking to the side, away from the aircraft centerline axis. In that situation, pilots may lose attitude awareness and thus develop spatial disorientation. A secondary concern is the possible effects of visual conflict between the apparent motion of traditional, nose-referenced flight symbology and the off-axis view of the outside world. Alternative symbologies will provide improved attitude awareness for HMDs when compared with the conventional inside-out symbology now used with head-up displays (HUDs), if the HUD symbology is used on a HMD. The 9 pilots were presented 48 randomly arranged unusual attitude conditions on a HMD. The three symbologies included: 1) the inside-out representation now used with fixed HUDs, which features a moving horizon and pitch ladder; 2) an outside-in display that depicts a moving aircraft relative to a fixed horizon; and 3) an inside-out novel symbology termed the grapefruit' display (GD). The background scene contained a mix of either a front view orientation or a side view one. Conditions were randomized within and across subjects. Subjective preferences were collected after the completion of all tasks. Analysis of variance repeated measures design revealed that stick input for the GD was significantly faster with fewer roll reversal errors than either of the other two. The time to recover to straight and level was significantly shorter for the front view orientation than the side view. Of the nine pilots, eight preferred the GD symbology as a method of presenting attitude information on the HMD. Results suggest the current HUD symbology is not the best way of displaying attitude information on the HMD. Given the conditions of this study, the best way of presenting the pilot with attitude information on the HMD is with the GD symbology."

Eriksson, L., Johansson, K., & von Hofsten, C. (2003). Peripheral vision effects on spatial orientation driven by focused depth. Presented at a poster session of the *47th Annual Meeting of the Human Factors and Ergonomics Society*. Denver, CO.

"Enhanced support of pilot spatial orientation (SO) could be achieved by presenting flight-adapted visual flow with conformal horizon in the peripheral visual field. This could be implemented on...HUDs...or...HMDs.... The [experimental] results indicate that focused depth drives the effects of peripheral visual flow on SO.

Fadden, S., Ververs, P. M., & Wickens, C. D. (2001). Pathway HUDS: Are they viable? *Human Factors 43*, 173-193.

Forbes, T.W. (1946). Auditory signals for instrument flying. *Journal of the Aeronautical Sciences*, May, 255-258.

Tones used to augment visual attitude displays and directions.

Gallimore, J.J., Brannon, N.G., Patterson, F.R., & Nalepka, J.P. (1999). Effects of FOV and aircraft bank on pilot head movement and reversal errors during simulated flight. *Aviation, Space, and Environmental Medicine, 70*(12), 1152-1160.

"Investigated the effects of field of view (FOV) and aircraft bank on pilot head movement and reversal error during simulated flight. It was hypothesized that as FOV decreased, there would be a significant reduction in Opto-Kinetic Cervical Reflex (OKCR)-induced head movement. Reduced FOV was also hypothesized to increase control reversal errors. To test this hypothesis 12 US military pilots completed simulated flight tasks in a stationary dome. Head tilt, pitch, and yaw were recorded as a function of aircraft bank and FOV (40, 60, and 100 degrees circular). The number of control reversal errors was analyzed to investigate signs of *spatial disorientation*. Results indicated that during visual meteorological condition (VMC) maneuvers pilots exhibited significant OKCR; however there were no significant differences among the 3 levels of FOV. FOV significantly affected head pitch movements under VMC and instrument meteorological conditions. Pilots yawed their heads in the direction of aircraft bank under VMC. Pilots committed 22 reversal errors out of 72 trials (30.55%). The magnitude of the error was largest in the 40 degree FOV condition.

Gallimore, J.J., & Liggett, K.K. (2000). *Implications of spatial sensory reflex research on primary flight display design.* San Antonio, TX: Spatial Disorientation Symposium.

OKCR occurs in VMC (when the horizon is visible), not in IMC. Apparently, it is due to the reflexive response to keep the horizon stable within the visual field. Head tilt from OKCR is likely to put the pilot's eyes outside the HUD eye box. Frame of reference is dictated by the pilots' attentional activities. Implications for transitions between different frames of reference are pertinent to HMD symbology; traditional symbology should not be used.

Gallimore, J.J., Patterson, F.R., Brannon, N.G., & Nalepka, J.P. (2000). The opto-kinetic cervical reflex during formation flight. *Aviation, Space, and Environmental Medicine, 71*(8), 812-821.

"Weather formation flight is a difficult task prone to episodes of spatial disorientation. Therefore, investigation of sensory reflexes under these conditions is critical. Recent studies have shown that the opto-kinetic cervical reflex (OKCR) occurs during VMC flight conditions and serves to establish the horizon retinal image as a stabilized primary visual-spatial cue. The purpose of this research was to investigate the OKCR and field of view (FOV) during formation flight under VMC and IMC. There were 2 experiments conducted in which a total of 26 pilots completed simulated flight tasks in a stationary dome. Head tilt was examined as a function of aircraft bank with unrestricted FOV in Experiment I. Experiment II examined head tilt under three FOV conditions (40 degrees, 60 degrees, and 100 approximately circular). During VMC maneuvers pilots exhibited significant OKCR. There were no differences in head tilt between Solo Figure 8 and Formation Figure 8 VMC conditions. Pilots did not tilt their heads under IMC Formation Flight. FOV did not significantly affect the OKCR. Pilots exhibit the OKCR during formation and solo VMC tasks. However, the OKCR is reduced when compared with low level navigation tasks, indicating a difference in the visual cues between tasks. Pilots do not exhibit OKCR during IMC flight; therefore, the OKCR will have an impact on formation flights in and out of clouds leading to sensory conflicts caused by repeated realignment of visual and vestibular systems."

Gawron, V., & Knotts, L. (1984). A preliminary flight evaluation of the peripheral vision display using the NT-33A aircraft. *Proceedings of the 28th Annual Meeting of the Human Factors Society*. Santa Monica, CA: Human Factors Society, 539-541.

Gillingham, K.K. (1992). The spatial disorientation problem in the United States Air Force. *Journal of Vestibular Research, 2*, 297-306.

"Spatial disorientation (SD) in flight wastes hundreds of millions of dollars worth of defense capability annually and continues to kill air-crew. SD results primarily from inadequacies of human visual and vestibular sensory systems in the flying environment; but other factors, such as task saturation and distraction, precipitate it. The United States Air Force is conducting a three-pronged research and development effort to solve the SD problem. We are attempting 1) to elucidate further the mechanisms of visual and vestibular orientation and disorientation, 2) to develop ground-based and inflight training

methods for demonstrating to pilots the potential for SD and the means of coping with it, and 3) to conceive and evaluate new ways to display flight control and performance information so that pilots can maintain accurate spatial orientation."

Gillingham, K.K., & Previc, F.H. (1993). *Spatial orientation in flight* (AL-TR-1993-0022). Wright-Patterson AFB, OH: Air Force Armstrong Laboratories.

Gilson, R.D., Ventola, R.W., & Fenton, R.E. (1975). A kinesthetic-tactual display for stall deterrence. In *Eleventh Annual Conference on Manual Control* (NASA TM X-62,464; under FAA contract DOT-FA74WA-3515). Moffett Field, CA: Ames Research Center, 440-451

Describes a device for the yoke or stick of an aircraft that pushes into the hand to indicate AOA.

Goldberg, M.E., Eggers, H.M., & Gouras, P. (1991). The ocular motor system. In E.R. Kandel, J.H. Schwartz, & T.M. Jessell (Eds.), *Principles of neural science*. Norwalk, CT: Appleton & Lange, 660-677.

Gomez, G. (2002). Spatial Disorientation: Something old & something new. In *Essays & Articles*. Found with Google search at: http://www.isamindia.org/essays/cme_spatial.shtml

Excellent historical overview and statistics. Vision gives 90% of the input to the brain for orientation. "The other senses play a supporting role in correct perception of aircraft orientation." "Visual dominance falls into two categories: the congenital type, in which ambient vision provides dominant orientation cues through natural neural connections and functions, and the acquired type, in which orientation cues are gleaned through focal vision and are integrated as a result of training and experience into an orientation percept. This complex skill must be developed through training and maintained through practice, and its fragility is one of the factors that make spatial disorientation such a hazard." "Visual cues from instruments utilize focal rather than the ambient mode of vision and therefore place greater demands on central processing resources." "A pilot's radio transmission that the aircraft controls are malfunctioning should not, therefore, be taken as conclusive evidence that a control malfunction caused a mishap: spatial disorientation could have been the real cause." "The basic concept of SD containment is to convert all Type I SD to Type II SD and prevent a Type II SD from becoming a Type III SD." The author also presents an SD Threat Checklist, which includes: "Flight over featureless terrain" (e.g., ocean or desert); and aircrew factors, such as "high arousal and anxiety which increase susceptibility to SD," drugs which impair a pilot's "ability to suppress nystagmus," and fatigue or task overload.

Gopher, D., Weil, M., & Barakeit, T. (1994). Transfer of skill from a computer game to flight. *Human Factors, 36*, 387-405.

Guedry, F.E. (1992). Perception of motion and position relative to the earth: An overview. *Annals of the New York Academy of Sciences, May 656*, 315-328. Found at: http://www.annalsnyas.org/cgi/content/abstract/656/1/315.

"Results of the five experiments are consistent with the following generalizations. Canal-mediated turn perception (pitch, roll, or yaw) in earth-horizontal or earth-vertical plane, is suppressed in direct relationship to the magnitude of a linear acceleration vector lying in the plane of a responding canal when the magnitude of the linear vector is constant or increasing and when its direction is either fixed or rotating in the same direction as the concomitant canal signal. Canal-mediated turn perception (pitch, roll, or yaw) is not suppressed by a coplanar linear vector that is counter-rotating relative to the canal signal. Change in perceived attitude (pitch, roll, or yaw) is very sluggish in the absence of concordant canal information; attitude change may not be an immediate otolith-mediated perceptual event but a slowly developing perception dependent upon cognitive appreciation of an immediate otolith angular position signal. Otolith phasic neural units, unreinforced by appropriate canal signals, may contribute more to a brief linear velocity component in perception than to rate of attitude change. Otolith-mediated attitude perception within a given earth-vertical plane can be distorted by strong coplanar angular velocity canal information. Once distorted, return to veridical attitude perception can be gradual because, in the absence of complimentary canal or visual information, recovery is dependent upon relatively slow cognitive appreciation of a prevailing otolith position signal. Several attractive hypotheses relating to the dynamics of attitude perception can only be tested by substantially more data on the dynamics of spatial orientation perception. Most of our objectives cannot be achieved without models that yield valid prediction of the dynamics of spatial orientation perception. All of the observations in these experiments were carried out in darkness, or, in the simulated catapult experiment, without external visual reference. Various forms of visual information will change the dynamics of spatial orientation perception. My discussion has been limited to consideration of the vestibular system, as though the canal and otolith systems completely controlled the dynamics of spatial orientation perceptions. Obviously other partners in the dynamics of postural control, including vision, proprioception, and expectation, must be included in this challenging field of research. Dedication to stereotyped ideas about objectivity in the 20th century has hindered advancement of knowledge on the dynamics of spatial orientation perception relative to rate of progress achieved by several scientists of the 18th and 19th centuries, who provided word pictures of perceived motions and tilts along with descriptions of the motions that engendered the pictures."

Haworth, L. A., & Seery, R. E. (1992). *Rotorcraft helmet mounted display symbology research* (SAE Technical Paper 921977). Warrendale, PA: Society of Automotive Engineers.

Haxby, J.V., Horwitz, B., Ungerleider, L.G., Maisog, J.M., Pietrini, P., & Grady, C.L. (1994). The functional organization of human extrastriate cortex: A PET-rCBF study of selective attention to faces and locations. *Journal of Neuroscience, 14*, 6336-6353.

Heinle, T.E. (2001). Spatial disorientation research. In *HSIAC Gateway, 12*(3), 1-3.

Highlights the SD problem and recent approaches to training and displays. "For the USAF alone, this [SD mishap rate] adds up to an average of $140 million annually."

Herdman, C.M., Johannsdottir, K.R., Armstrong, J., Jarmaz, J., LeFevre, J., & Lichacz, F. (2000). Mixed-up but flyable: HMDs with aircraft- and head- referenced symbology. In D. Harris (Ed.), *Proceedings of the Third International Conference on Engineering Psychology and Cognitive Ergonomics, 5.* Edinburgh, Scotland: Ashgate, 73-80.

Hess, R.A. (1980). Structural model of the adaptive human pilot. *Journal of Guidance and Control, Vol. 3*(5), 416-423.

This article suggests a general model and formulas for signal processing in pursuit and compensatory tracking tasks, which are helpful for explaining observed data, but are not as good at predicting performance.

Holmes, S.R., Bunting, A., Brown, D.L., Hiatt, K.L., Braithwaite, M.G., & Harrigan, M.J. (2003). Survey of spatial disorientation in military pilots and navigators. *Aviation, Space, and Environmental Medicine, 74*(9), 957-965.

"752 UK aviators answered an SD survey that showed 92% of respondents experienced the Leans, the most frequently experienced SD event from the survey. Next most frequent was loss of horizon due to atmospheric conditions (82%), then misleading altitude cues (79%), sloping horizon (75%), and distraction-induced SD (66%). The researchers correlated SD experiences with training (ground and in-flight) and found a significant correlation between training and SD recognition and severity. The researchers concluded that in-flight training was most beneficial and should be tailored to the specific aircraft and circumstances (e.g., use of NVGs)."

Howard, I.P. (1986). The perception of posture, self-motion and the visual vertical. In K.R.Boff, L.Kaufman, & J.P. Thomas (Eds.), *Handbook of Perception and Human Performance* (Volume I). New York: John Wiley & Sons, 18.1-18.62.

Visual-vestibular interactions, dampening effects, and thresholds of detectable motions.

International Standards Organization (2002). *ISO 14915-3:2002(E), Annex D: Design issues and cognitive background.*

Human signal processing bottlenecks and an assertion: "Generally our eyes are drawn to moving shapes, then complex, different, and colorful objects."

Ivanov, A.I., & Lapa, V.V. (2002). The effect of mobility of the information field of the helmet-mounted indicator on pilot's efficiency. *Aviakosm. Ekolog. Med., 36*(4), 37-40.

"Results of an experimental investigation of pilot's efficiency with the use of a helmet-mounted indicator (HMI) are reported. Displacement of the HMI information field in consequence of head movements in search for external objects and target acquisition was shown to impact reliability of spatial orientation and cause difficulties during construction and realization of aircraft control movements. These difficulties are ascribed to impairment of functioning of the human 'body scheme' (internal systems of coordinates) and modification of the geometric relations of the true and HMI displayed horizon. The conclusion is that to improve efficiency of pilots using HMI designed should be a device which will align the HMI information field with the longitudinal cabin axis after each head movement."

Jia, H.B., Yu, L.S., Bi, H.Z., Wang, K.N., Liu, Z., & Xie, S.J. (2001). Ground simulation of the G-excess illusion. *Space Medicine and Medical Engineering, 14*(2), 88-91.

"To observe the subjects' perception of orientation following certain head movements or change of simulator cab attitude in hypergravity (HG), and assess the feasibility of simulating G-excess illusion on the ground by a centrifuge-like Spatial Disorientation (SD) simulator. 1.6 G force field was generated by planetary rotation of the simulator. Perception of orientation of the cab were collected from twelve male pilots' report following their heads pitch movements in pitch plane or cab attitude changes in roll plane under 1.6 G. While making a pitch-up head movement, the pilots experienced a 63.8 degrees +/- 48.3 degrees pitch-up attitude change of the cab in pitch plane, and when the cab was tilted left 20 degrees, pilots experienced a tilt-left perception of 48.6 degrees +/- 39.4 degrees in roll plane. Although there's strong Coriolis effects onboard the SD simulator under 1.6 G, most pilots experienced the G-excess illusion. It demonstrated that it was feasible to use the centrifuge-like device to generate this kind of illusion on the ground."

Johnson, K.R. (2000). *Spatial disorientation in military aviation.* Presented at the Spatial Disorientation Symposium, San Antonio, TX. Found at: www.spatiald.wpafb.af.mil/library_ san.asp.

Johnson, S.L., & Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors, 14*, 107-129.

Kaczmarek, K.A. (2000). Electrotactile adaptation on the abdomen: Preliminary results. *IEEE Transactions on Rehabilitation Engineering, 8*(4), 499-505.

"Electrotactile (electrocutaneous) stimulation at currents greater than sensation threshold causes sensory adaptation, which temporarily raises the sensation threshold and reduces the perceived magnitude of stimulation. After 15 min[utes] of moderately intense exposure to a conditioning stimulus (10 s[econds] on, 10 s[econds] off), the sensation threshold elevation for seven observers was 60-270%, depending on the current, frequency, and number of pulses in the burst structure of the conditioning stimulus. Increases in any of these parameters increased the sensation threshold elevation. Adaptation and recovery were each complete in approximately 15 min[utes]."

Kandel, E.R. (1991). Perception of motion, depth, and form. In E.R. Kandel, J.H. Schwartz, & T.M. Jessell (Eds.), *Principles of neural science* (3rd ed.). Norwalk, CT: Appleton & Lange, 440-466.

Kandel, E.R., Schwartz, J.H., & Jessell, T.M. (Eds.) (1991). *Principles of neural science* (3rd ed.). Norwalk, CT: Appleton & Lange.

Kehoe, N.B. (1985). Colonel Kehoe's spatial disorientation (SD) incident in an F-15 during VMC. In *Proceedings of the Aircraft Attitude Awareness Workshop*. Wright-Patterson AFB, OH: Flight Dynamics Laboratory (October 8-10), pages 1-5-1 to 1-5-4.

Personal experience: Noise cue alerted pilot to unusual attitude – going very fast.

Kelly, J.P. (1991). The neural basis of perception and movement. In E.R. Kandel, J.H. Schwartz, & T.M. Jessell (Eds.), *Principles of neural science*. Norwalk, CT: Appleton & Lange, 283-295.

Kirkham, W.R. (1978). Spatial disorientation in general aviation accidents. *Aviation, Space, and Environmental Medicine, 49,* 1080-1086.

"Spatial disorientation (SD) refers to an incorrect self-appraisal of the attitude or motion of the pilot and his aircraft with respect to the earth. This paper defines elements of SD problems as encountered in general civil aviation. Accident reports made by the National Transportation Safety Board for a recent 6-year period were reviewed. Statistical computations were made relating SD to fatal accidents. Small fixed-wing aircraft (under 12,500 lb) accounted for 97.3 percent of all SD accidents. Inclement weather was associated with 42 percent of all fatal accidents, and SD was a cause or factor in 35.6 percent of these cases. Non-instrument-rated pilots were involved in 84.7 percent of SD weather-involved accidents. These and other data attest to the importance of this psychophysiological phenomenon (SD) in flight safety. Suggestions are made of ways to improve pilots' awareness and understanding of this problem."

Knapp, C.J., & Johnson, R. (1996). F-16 Class A mishaps in the U.S. Air Force, 1975-93. *Aviation, Space, and Environmental Medicine, 67*(8), 777-783.

"All USAF F-16 fighter Class A (major) aircraft mishaps from 1975-93 were analyzed; using records from the U.S. Air Force Safety Agency (AFSA). There were 190 Class A mishaps involving 204 F-16's and 217 aircrews during this 19-yr period. The overall Class A rate was 5.09 per 100,000 flight hours, more than double the overall USAF rate. The mishaps are categorized by year, month, time of day and model of aircraft in relation to mishap causes as determined and reported by AFSA. Formation position, phase of flight and primary cause of the mishap indicate that maneuvering, cruise and low-level phases account for the majority of the mishaps (71%), with air-to-air engagements associated with a higher proportion of pilot error (71%) than air-to-ground (49%). Engine failure was the number one cause of mishaps (35%), and collision with the ground the next most frequent (24%). Pilot error was determined as causative in 55% of all the mishaps. Pilot error was often associated with other non-pilot related causes. Channelized attention, loss of situational awareness and spatial disorientation accounted for approximately 30% of the total pilot error causes found. Pilot demographics, flight hour/sortie profiles, and aircrew injuries are also listed. Fatalities occurred in 27% of the mishaps, with 97% of those involving pilot errors."

Kovalenko, P.A. (1991). Psychological aspects of pilot spatial orientation. *ICAO Journal, 46*(3), 18-23.

"Researchers examined the psychological aspects of pilot spatial orientation to aircraft attitude. Study participants completed questionnaires and made drawings of view-from-the-ground and aircraft front window and of attitude indicators, then made flights in a simulator or aircraft with unknown pitch attitude. Analysis of data indicates that pilots favored a view-from-the-ground indicator. The main drawback to the view-from-the-aircraft indicator was mobility of image. The study also examined spatial-orientation techniques pilots use in different flight phases and identified seven factors in effective spatial-orientation techniques. Other components of the study included a comparison of the manipulative capability of pilots and nonprofessional participants and pilot recall of a set of images from long-term and operational memory."

Lappe, M. (1997). Analysis of self-motion by parietal neurons. In P. Thier & H.O. Karnath (Eds.), *Parietal lobe contributions to orientation in 3D space.* Heidelberg: Springer-Verlag, 597-618.

Lawson, B.D., Kass, S.J., Kennedy, R.S., Muth, E.R., & Smith, S.A. (2002). Vestibular stimuli may degrade situation awareness even when spatial disorientation is not expressed. *Human Factors and Medicine Symposium, Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures Panel.* La Caruna, Spain: NATO Research & Technology Agency.

LeBlaye, P., Roumes, C., Fornette, M.P., & Valot, C. (2002). *Head up displays symbology (HUD): Pre-normative study for GFAC/SFACT* (DCSD TR 2/05007). Paris: ONERA.

"This report is the final report of the first phase of a study of head up displays (HUD) symbology conducted for DGAC/SFACT, in the frame of its pre normative research program for civil aviation safety. This report describes the main steps and results of the study:
1. Comparative analysis of the JAA and FAA regulations concerning HUD in general, and more especially, the specifications about their symbology
2. State of the interpretation of the existing regulations, through the interviews of certification experts
3. Comparative analysis of the symbologies of existing HUD products and comparison with the requirements of the regulation
4. Current state of the operational use of HUD, through the available safety reporting systems and interviews with the users
5. Synthesis of the lack of the regulation in regard with the needs of the certification experts and with the operational difficulties encountered by the users."

Levison, W., Elkind, J., & Ward, J. (1971). *Studies of multi-variable manual control systems: A model for task interference* (NASA contractor report 1746). Washington, DC: NASA.

Levy, J.L., Foyle, D.C., & McCann, R.S. (1998). Performance benefits with scene-linked HUD symbology: An attentional phenomenon? In *Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: Human Factors Society.

Liggett, K.K., & Gallimore, J.J. (2002). An analysis of control reversal errors during unusual attitude recoveries using helmet-mounted display symbology. *Aviation, Space, and Environmental Medicine, 73*(2), 102-111.

> "Spatial disorientation (SD) refers to pilots' inability to accurately interpret the attitude of their aircraft with respect to Earth. Unfortunately, SD statistics have held constant for the past few decades, through the transition from the head-down attitude indicator (AI) to the head-up display (HUD) as the attitude instrument. The newest attitude-indicating device to find its way into military cockpits is the helmet-mounted display (HMD). HMDs were initially introduced into the cockpit to enhance target location and weapon-pointing, but there is currently an effort to make HMDs attitude reference displays so pilots need not go head-down to obtain attitude information. However, unintuitive information or inappropriate implementation of on-boresight attitude symbology on the HMD may contribute to the SD problem. The occurrence of control reversal errors (CREs) during unusual attitude recovery tasks when using an HMD to provide attitude information was investigated. The effect of such errors was evaluated in terms of altitude changes during recovery and time to recover. There were 12 pilot-subjects who completed 8 unusual attitude recovery tasks. Results showed that CREs did occur, and there was a significant negative effect of these errors on absolute altitude change, but not on total recovery time. Results failed to show a decrease in the number of CREs occurring when using the HMD as compared with data from other studies that used an AI or a HUD. Results suggest that new HMD attitude symbology needs to be designed to help reduce CREs and, perhaps, SD incidences."

Liggett, K.K., Reising, J.M., & Hartsock, D.C. (1999). Development and evaluation of a background attitude indicator. *International Journal of Aviation Psychology, 9*, 49-71.

Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science, 240*, 740-749.

Long, J. (2002). Heads up on heads-up: SDO hazards from moving tape HUD symbology. *Flying Safety*. Kirtland AFB, NM: Air Force Safety Center, 4-9.

> This article describes roll vection induced by HUD airspeed and altitude "tapes" moving in opposite directions during a rapid descent.

Lyons, T.J., Ercoline, W.R., Freeman, J.E., & Gillingham, K.K. (1993). Epidemiology of United States Air Force spatial disorientation accidents: 1990-1991. In *Aircraft accidents: Trends in aerospace medicine investigation techniques* (AGARD CP 532:31-1 to 31-11). Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development.

"Spatial disorientation (SD) continues to be a contributing factor to a fairly constant proportion of military aircraft accidents. The United States Air Force (USAF) fielded a new accident investigation reporting form in July 1989, which for the first time specified SD Type 1, Type 2, and Type 3 as possible causes of aircraft accidents. Of a total of 91 major accidents that occurred over the2-year period beginning in October 1989, SD contributed significantly to 13 (14 percent). Although this percentage is higher than that reported in previous studies, the actual rate of SD accidents per 100,000 flying hours (.1843) is lower than previously reported. Type 1 SD was the cause of all 13 accidents; 9 of the 13 were fatal; 6 occurred in night or instrument meteorological conditions (IMC) conditions; and 11 involved cockpit attention problems, such as inattention, distraction, or channelized attention. Pilot inexperience did not appear to be a factor: average total flying time for the 13 pilots was 1,687 hours. Coding for SD on accident investigation reporting forms was not consistent. There were both individual differences between flight surgeons and pilots, and trends in reporting overtime. There is, however, a consensus that SD represents a major problem in military aviation. A scientific approach to this important problem would be facilitated if agreement could be reached on definitional and semantic issues."

Lyons, T.J., Ercoline, W.R., Freeman, J.E., & Gillingham, K.K. (1994). Classification problems of U.S. Air Force spatial disorientation accidents, 1989-91. *Aviation, Space, and Environmental Medicine, 65*, 147-152.

Statistics for SD accidents and illusions, but inconsistent reporting makes it difficult to state the magnitude of specific issues.

Macurdy, J.T. (1934). Disorientation and vertigo, with special reference to aviation. *British Journal of Psychology, 25*, 42-54.

Malinin, I., Ercoline, W.R., Previc, F.H., & Malinina, H. (2000). *The consequences of adding runway symbology to the head-up display*. Presented at the Spatial Disorientation Symposium, 15-17 November, 2000, San Antonio, TX. Found at: http://www.spatiald.wpafb.af.mil/ Primary%20Flight%20Displays/malininr.pdf

While the focus of this presentation was on CFIT accident prevention using HUD symbols, it offers a taxonomy of a pilot's processing of flight symbology to maintain spatial attitude awareness during IFR and VFR flight.

McCarley, J.S., Wickens, C.D., Goh, J., & Horrey, W.J. (2002). A computational model of attention/situation awareness. In *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: HFES.

"A computational model of attention and situation awareness (SA) was developed and used to predict pilot errors…. The model incorporates a low-level perception/attention module and a higher-level belief-updating module. Attentional scanning is controlled by bottom-up and top-down processes, with the effectiveness of top-down guidance varying as a function of SA. Information sampled by the low-level module is fed forward to the

higher-level module for consolidation within a working memory representation of the pilot's situation, with the quality of this representation reflecting the pilot's level of SA. The model was validated by comparing its predictions to the behavior of pilots.... Results indicate that the model successfully predicts the improved performance associated with display augmentations, and provides construct validity regarding the effects of visibility, distraction, and degraded information quality."

McGrath, B.J. (2000). *Tactile instrument for aviation* (Naval Aerospace Medical Research Laboratory Monograph 49). Pensacola, FL: NAMRL.

Meehan, J.W. (2001). Advanced display technologies: What have we lost? *HSIAC Gateway 12*(3), 13-14.

Attentional capture and fixation as sources of problems related to LSA and SD.

Melzer, J.E., & Moffitt, K. (1997). HMD design - Putting the user first. In J.E. Melzer and K. Moffitt (Eds.), *Head mounted displays: Designing for the user.* New York: McGraw-Hill.

Merryman, R.F.K., & Cacioppo, A.J. (1997). The optokinetic cervical reflex in pilots of high-performance aircraft. *Aviation, Space, and Environmental Medicine, 68*(6), 479-487.

"While modifications of the cockpit attitude displays are unlikely to occur in the near future, the ease by which the symbology of new displays (i.e., helmet-mounted displays) can be changed makes them the prime candidates for 'OKCR-friendly' design changes. Caution must be taken, however, since multiple attitude displays of differing types may prevent resolution or add to spatial disorientation. Therefore, all attitude displays within the vehicle should be compatible with a singular frame of reference and this frame of reference should be determined experimentally and include the OKCR response."

Milgram, P., & Colquhoun, H., Jr. (1999). A taxonomy of real and virtual world display integration. In Y. Ohta and H. Tamura (Eds.), *Mixed reality – merging real and virtual worlds.* Berlin: Springer-Verlag.

Nall (1999). *1999 Nall Report: Accident trends and factors for 1998.* Report found at http://www.aopa.org/asf/publications/99nall.html.

"Spatial disorientation occurs when a pilot is deprived of visual references to determine the aircraft's orientation in three-dimensional space. Any conditions which deprive the pilot of natural, visual references to maintain orientation, such as clouds, fog, haze, darkness, or terrain/sky backgrounds with indistinct contrast (such as arctic whiteout or clear, moonless skies over water) can rapidly bring about spatial disorientation. Without a means of controlling the airplane with reference to the earth's surface, loss of control is imminent. The only preventive measure is to rely on references based on the aircraft's instruments. The aircraft must be adequately equipped and maintained and the pilot must be sufficiently trained to fly solely by reference to instruments.

"In 1998, six accidents contained specific references to spatial disorientation in the sequence of events or narrative sections of their reports. This number is, however, what statisticians call a "lower bound" on the true number of accidents in which spatial disorientation was a significant factor. The conditions surrounding a number of other weather-related accidents suggest that spatial disorientation might have been contributory there as well.

"A detailed analysis of accidents over a ten-year period (1987-1996) with an emphasis on spatial disorientation as a cause or significant contributory factor reveals a much higher involvement of this factor than suggested by the direct references in the 1998 reports. During this period, there was an average of almost 37.6 accidents per year, of which 33.9 were fatal. At this rate, there is one fatal spatial disorientation accident every eleven days. Over 90 percent of all the accidents during this time in which spatial disorientation was a factor resulted in fatalities.

"Typically, these accidents are suffered by noninstrument-rated pilots attempting to complete VFR flights in instrument meteorological conditions. At least one accident in 1998, however, occurred when an experienced instrument-rated pilot in a well-equipped turbine-powered airplane became disoriented during the visual portion of a circling IFR approach. In this case, a moonless night exacerbated the weather conditions."

Navathe, P.D., & Singh, B. (1994a). Prevalence of spatial disorientation in Indian Air Force aircrew. *Aviation, Space, and Environmental Medicine, 65*(12), 1082-1085.

The 1st Aero Medical Training Centre has surveyed aircrew of the Indian Air Force to determine the prevalence of Spatial Disorientation (SD), as related to aircraft stream, age, flying experience, geographical location and other operationally significant variables. The reported prevalence of SD is 75% among fighter aircrew, 64% in transport aircrew, and 55% in helicopter aircrew. Whereas the prevalence of SD does not appear to vary significantly with age and flying experience, it is higher in fully operational pilots and in pilots returning to flight duties after a ground tenure, as compared to ab-initio and type-converting pilots.

Navathe, P.D., & Singh, B. (1994b). An operational definition for spatial disorientation. *Aviation, Space, and Environmental Medicine, 65*(12), 1153-1155.

Nelson, W.T., Hettinger, L.J., Cunningham, J.A., Brickman, B.J., Haas, M.W., & McKinley, R.L. (1998). Effects of localized auditory information on visual target detection performance using a helmet mounted display. *Human Factors, 40*, 452-460.

Niall, K.K. (2002). Laser projection versus a CRT display in the visual perception of aircraft aspect. *Human Factors, 44*(4), 630-643.

"High-resolution visual displays have been designed for flight simulation so that observers may judge the aspect angle of aircraft at far distances. The present experiment com-

pares two display devices as untrained observers judge the spatial orientation of two target aircraft: F-15 and F-16 jets. The display devices are a prototype direct-write microlaser projector and an SXGA-format CRT display. Observers' accuracy of aircraft identification is better with the laser projector, and recognition response times are faster. A simple rule was found to fit the observers' response times; it is expressed in terms of a statistic on the autocorrelation of black-and-white silhouette images of aircraft. Observers' estimates of aspect are biased by the laser projector, whereas observers' estimates of aspect are accurate on average with the SXGA display. This bias in estimation of aspect may be attributable to variations in line brightness introduced by the laser projector. Actual or potential applications of this research include the evaluation of high-resolution visual displays for the training of basic fighter maneuvers with military jet pilots."

NTSB (2002). *Aircraft accident brief: Cessna 335, N8354N near Hillsboro, Missouri, October 16, 2000* (AAR-02-02, adopted 6/5/02). Washington, D.C.: author.

Ocker, W.C., & Crane, C.J. (1932). *Blind flight in theory and practice.* San Antonio, TX: Naylor.

O'Hare, D., & Roscoe, S.N. (1991). *Flight deck performance: The human factor.* Ames, IA: Iowa State University Press.

Leans and head tilt to false (sensed) horizon – different from OKCR, since IMC, not VMC. The Leans involves the tilting of the head orthogonal to the "apparent" horizon as signaled through the vestibular system, when that system has been co-opted by the illusion (washout). This is different from OKCR. In short, the head will always automatically orient itself orthogonal to the inferred/perceived horizon. In VMC, this is explicit, and accounts for the OKCR when the aircraft rolls. In IMC without illusions, the apparent horizon, in a coordinated turn, is parallel with the wings of the aircraft. Hence the OKCR is not observed when the airplane banks (Gallimore's finding). After washout, the apparent horizon is at an angle with the true horizon. Hence the head orients to this apparent horizon after the plane stabilizes (accounting for the leans).

Okada, T., Grunfeld, E., Shallo-Hoffmann, J., & Bronstein, A.M. (1999). Vestibular perception of angular velocity in normal subjects and in patients with congenital nystagmus. *Brain, 122*(7), 1293-1303.

"A technique is described for the assessment of vestibular sensation. The two main goals of the study were (i) to compare the perception of angular velocity with the eye velocity output of the vestibulo-ocular reflex and (ii) to study vestibular function in patients with congenital nystagmus; this was needed since most previous studies, based on eye movement recordings, have been inconclusive. Subjects indicated their perceived angular velocity by turning by hand a wheel connected to a tachometer. The vestibular stimuli used consisted of sudden deceleration from rotation at a constant horizontal velocity of 90°/s ('stopping' responses). Eye movements were recorded simultaneously with electro-oculography. In normal subjects the perceived angular velocity decayed from the moment of deceleration in an exponential fashion. The mean time constant of sensation

decay was ~16 s. Eye movement velocity decayed with a similar exponential trajectory (time constant 16 s). Congenital nystagmus patients showed markedly shortened vestibular sensation (mean time constant 7 s). The following conclusions can be drawn: (i) the similarity of the eye velocity and perceptual responses suggests that these two systems receive a vestibular signal which has been similarly processed; (ii) the time constant of the responses indicates that this vestibular signal probably originates in the same brainstem 'velocity storage' integrator; (iii) the technique described is useful for clinical assessment of vestibular function, particularly in patients with ocular motility disorders; (iv) patients with congenital nystagmus have short vestibular time constants, which is probably due to changes induced in velocity storage processing by the persistent retinal image motion present in these patients."

Otakeno, S., Matthews, R.S., Folio, L., Previc, F.H., & Lessard, C.S. (2002). The effects of visual scenes on roll and pitch thresholds in pilots versus nonpilots. *Aviation, Space, and Environmental Medicine, 73*(2), 98-101.

"Previous studies have indicated that, compared with non-pilots, pilots rely more on vision than 'seat-of-the-pants' sensations when presented with visual-vestibular conflict. The objective of this study was to evaluate whether pilots and non-pilots differ in their thresholds for tilt perception while viewing visual scenes depicting simulated flight. This study was conducted in the Advanced Spatial Disorientation Demonstrator (ASDD) at Brooks AFB, TX. There were 14 subjects (7 pilots and 7 nonpilots) who recorded tilt detection thresholds in pitch and roll while exposed to sub-threshold movement in each axis. During each test run, subjects were presented with computer-generated visual scenes depicting accelerating forward flight by day or night, and a blank (control) condition. The only significant effect detected by an analysis of variance (ANOVA) was that all subjects were more sensitive to tilt in roll than in pitch [$F(2,24) = 18.96$, $p < 0.001$]. Overall, pilots had marginally higher tilt detection thresholds compared with non-pilots ($p = 0.055$), but the type of visual scene had no significant effect on thresholds. In this study, pilots did not demonstrate greater visual dominance over vestibular and proprioceptive cues than non-pilots, but appeared to have higher pitch and roll thresholds overall. The finding of significantly lower detection thresholds in the roll axis vs. the pitch axis was an incidental finding for both subject groups."

Pancratz, D.J., Bomar, J.B., Jr., & Raddin, J.H., Jr. (1994). A new source for vestibular illusions in high agility aircraft. *Aviation, Space, and Environmental Medicine, 65*(12), 1130-1133.

"The enhanced maneuverability aircraft of the future will expose pilots to combinations of conventional translational accelerations as well as extraordinary angular accelerations. This flight regime, combined with the intense concentration required for combat maneuvering, will make motion-induced illusions more perilous than in existing aircraft. Although there are many causes for disorientation, theoretical analysis indicates two in particular, the 'G-excess' and 'cross-coupling' illusions, may be invoked by a new and distinctly different stimulus. These two illusions, which are both typically induced by motion of the pilot's head, may in addition be created by rotation of the aircraft with respect to its flight path. After comparing typical pilot head movements to projected decoupled angular motion capabilities of supermaneuverable aircraft, we conclude that the potential exists for G-excess or cross-coupling illusions in a high agility aircraft independent of pilot head motion with respect to the aircraft.

Patterson, F.R., Cacioppo, A.J., Gallimore, J.J., Hinman, G.E., & Nalepka, J.P. (1997). Aviation spatial orientation in relationship to head position and attitude interpretation. *Aviation, Space, and Environmental Medicine, 68*(6), 463-71.

Pilots exhibit OKCR in VMC, not in IMC, in fixed-base simulator. "Conventional wisdom describing aviation spatial awareness assumes that pilots view a moving horizon through the windscreen. This assumption presupposes head alignment with the cockpit 'Z' [vertical] axis during both visual (VMC) and instrument (IMC) maneuvers. Even though this visual paradigm is widely accepted, its accuracy has not been verified. The purpose of this research was to determine if a visually induced neck reflex [OKCR] causes pilots to align their heads toward the horizon, rather than the cockpit vertical axis. Some 14 military pilots completed two simulated flights in a stationary dome simulator. The flight profile consisted of five separate tasks, four of which evaluated head tilt during exposure to unique visual conditions and one examined occurrences of disorientation during unusual attitude recovery. During simulated visual flight maneuvers, pilots tilted their heads toward the horizon ($p < 0.0001$). Under IMC, pilots maintained head alignment with the vertical axis of the aircraft. During VMC maneuvers pilots reflexively tilt their heads toward the horizon, away from the Gz axis of the cockpit. Presumably, this behavior stabilizes the retinal image of the horizon (1 degree visual-spatial cue), against which peripheral images of the cockpit (2 degrees visual-spatial cue) appear to move. Spatial disorientation, airsickness, and control reversal error may be related to shifts in visual-vestibular sensory alignment during visual transitions between VMC (head tilt) and IMC (Gz head stabilized) conditions. The current moving horizon attitude displays lack in both pictorial reality and control motion compatibility. Forced spatial reversal during VMC to IMC transition may contribute to *disorientation*, *reversal error*, and *task saturation*."

Pines, M. (2003). The mystery of smell: The vivid world of odors. In *Seeing, hearing, and smelling the world* (report from the Howard Hughes Medical Institute). Found at: http://www.hhmi.org/senses/d110.html

"Smells…retain an uncanny power to move us." The article also describes how odor and taste signals reach the brain.

Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological Bulletin, 124*, 123-164.

Previc, F.H. (2000a). Neurophysiological guidelines for aircraft control stations. *IEEE Engineering in Medicine and Biology, March/April*, 81-87.

Previc, F.H. (2000b). *In search of ambient vision*. San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/MechanismsStudies/previc.pdf

Defines ambient vision and explains its role in orientation and the perception of motion.

Previc, F.H., & Ercoline, W.R. (1999). The "outside-in" attitude display concept revisited. *The International Journal of Aviation Psychology, 9*(4), 377-401.

A moving aircraft (outside-in) attitude display has been shown superior to the widely used inside-out (moving horizon) attitude display. Novice and trained pilots both perform better with the outside-in display when recovering from unusual attitudes. Since it has proven very difficult to change the status quo, this display perspective may be well suited for off-axis HMD applications, UAV control, and so-called global situation displays. Since the outside-in display reduces roll-reversal errors, the authors cite statistics to show the importance of reducing such errors: "A 5% to 10% roll-reversal error in recovering from unusual attitudes has implications for military and civilian aviation. Bank illusions are reportedly the most prevalent form of spatial disorientation in pilots…and spatial disorientation remains a leading cause of military and civilian aircraft losses. During the 1980s, for instance, spatial disorientation resulted in 81 USAF Class A mishaps, or approximately 12% of all Class A mishaps and nearly 25% of Class A mishaps attributable to operator-related causes…. Spatial disorientation, together with loss of situational awareness, accounted for a staggering 85% of all USAF operator-related mishap fatalities during this same period…. Over that same period, 112 U.S. Navy Class A mishaps (representing about 15% of the entire Navy total) were attributed to either possible (61), probable (18), or definite (33) spatial disorientation…. In general aviation, the percentage of all mishaps due to spatial disorientation is 2% to 2.5%, but the percentage of fatal mishaps due to disorientation is at least 10%.... Roll-reversal errors, in particular, are believed to have contributed to many spatial disorientation mishaps over the years, including several commercial airline disasters…and at least two U.S. Navy…and two USAF crashes in 1996 and 1997. It is disturbing that in advanced aircraft that cost tens of millions of dollars or more, pilots still cannot properly orient by means of their attitude instruments when disoriented and must resort to the well-known 'waffling' with the stick to determine the correct righting direction during unusual-attitude recoveries. Not surprisingly, the spatial disorientation mishap rate in the USAF has not fundamentally changed over the past three decades."

Previc, F.H., & Ercoline, W.R. (2001). Trends in spatial disorientation research. *Aviation Space and Environmental Medicine, 72*(11), 1048-1050.

A 60-year retrospective categorization of the SD literature into 347 articles into altitude instrumentation, SD incidence and SD training. A dramatic increase in SD research began in the early 90s.

Raj, A.K., Kass, S.J., & Perry, J.F. (2000). Vibrotactile displays for improving spatial awareness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Santa Monica, CA: Human Factors Society, 181-184.

Reed, R.R. (2003). Molecular approaches to olfaction. In *In the lab: HHMI investigators.* Found at http://www.hhmi.org/research/investigators/reed.html. Last updated February 4, 2003.

"Chemosensation, the detection of chemicals in the environment, is among the oldest of the sensory systems.... These external stimuli are converted into nerve impulses and subsequent cognitive and behavioral responses."

Regan, D. (1995). Spatial orientation in aviation: Visual contributions. *Journal of Vestibular Research, 5*(6), 455-471.

"Misjudgment of spatial orientation is reported to be an important factor in a substantial proportion of aviation accidents. The likelihood of such misjudgment is particularly high when there are conflicting interactions between labyrinthine and visual signals. In a maneuvering aircraft, visual information is often a crucial factor in the pilot's ability to judge the aircraft's altitude and position with respect to external and terrain features. A body of research evidence supports the following conceptual framework. (1) The human visual system processes a limited number of visual dimensions almost independently of each other (for example, color, luminance, spatial frequency, orientation, changing size, motion in depth, time to contact). (2) Each of these selective sensitivities shows considerable inter-subject variability. (3) Inter-subject variability is far from perfectly correlated across the set of selective sensitivities. This paper discusses the relevance of this framework for predicting, first the specific situations in which visual judgments are most likely to occur and, second, which individual pilots are most likely to make the visual misjudgments."

Reising, J.M., Liggett, K.K., & Munns, R.C. (1999). Controls, displays, and workplace design. In D.J. Garland, J.A. Wise, & V. D. Hopkin (Eds.), *Handbook of Aviation Human Factors*. Mahwah, NJ: Lawrence Erlbaum Associates, 327-354.

Display concepts for unusual attitude recovery. Crew station design process emphasizes modeling, information requirements, evaluations, and traceability used in an iterative fashion.

Rochlis, J.L., & Newman, D.J. (2000). A tactile display for International Space Station (ISS) extravehicular activity (EVA). *Aviation, Space, and Environmental Medicine, 71*, 571-8.

"The Tactor Locator System (TLS) is a non-intrusive, intuitive display capable of conveying position and velocity information via a vibrotactile stimulus applied to the subject's torso and neck.... The TLS was designed to provide somatosensory cues to complement the visual system..."

Rouse, W.B., & Gopher, D. (1977). Estimation and control theory: Application to modeling human behavior. *Human Factors, 19*(4), 315-329.

While not specific enough for our SO/SD modeling, this article describes formulas for human-machine system models.

Roscoe, S.N. (1968). Airborne displays for flight and navigation. *Human Factors, 10,* 321-332.

Roscoe, S.N. (2002). Ergavionics: Designing the job of flying an airplane. *International Journal of Aviation Psychology, 12*(4), 331-339.

Roscoe, S.N., & Williges, R.C. (1975). Motion relationships in aircraft attitude and guidance displays: A flight experiment. *Human Factors, 17,* 374-387.

Rosenzweig, M.R., Breedlove, S.M., & Leiman, A.L. (2002). *Biological Psychology* (3rd ed.). Sunderland, MA: Sinauer Associates, Inc.

Rupert, A.H. (2000). Tactile situation awareness system: proprioceptive prostheses for sensory deficiencies. *Aviation, Space, and Environmental Medicine, 71*(9), A92-99.

> "Pilots and astronauts do not experience spatial disorientation in normal day-to-day terrestrial activities. On the ground, the perception of position and motion is determined by central nervous system integration of concordant and redundant information from multiple sensory channels (somatosensory, vestibular and visual) which collectively yield veridical perceptions. In the acceleration environments experienced by pilots and astronauts, the somatosensory and vestibular senses frequently present false but concordant information concerning the direction of gravity or down. When presented with conflicting sensory stimuli, it is normal for pilots and astronauts to experience episodes of disorientation. Visual instruments and displays developed over the past 70 yr have not solved the problem. A simple solution to maintain spatial orientation is to provide true information using the same sensory channels we use so successfully on Earth. The Tactile Situation Awareness System (TSAS) developed by NASA and the U.S. Navy uses a matrix of mechanical tactile stimulators (tactors) applied on the torso and limbs to convey orientation cues (e.g., gravity vector) in an intuitive fashion to the skin. A series of in-flight experiments to validate and test a variety of tactile displays and concepts has been carried out in both helicopters and fixed wing aircraft. Pilots were able to fly complex maneuvers with no instruments or outside visual references (blindfolded) with less than 20 min of training. Recovery from unusual attitudes solely by tactile cues was trivial. Lab tests have shown the TSAS improves performance under conditions of high workload. When orientation information is presented via intuitive tactile displays spatial orientation is easily maintained in altered sensory conditions including unusual acceleration environments."

Schneider, E., & Glasauer, S. (date unknown). *Temporal summation of vestibular afferents in humans affects perceptional threshold of rotation around the yaw axis*. Found on 11/6/2003 at: http://www.nefo.med.uni-muenchen.de/~eschneider/threshold/

> "When acoustical, visual and somatosensorial cues are lacking, the perception of whole body rotation about the yaw axis relies on the stimulation of the horizontal semicircular canals. On the basis of their mechanics, which can be described by a second-order differential equation, their afferent output basically reflects angular velocity. Although

physiological studies of these afferents have not established a mechanical or neural threshold, humans perceive rotatory movements only at angular velocities above a threshold of 1 to 4 deg/sec.

"The experimental data in the literature reveals that the behavior of vestibular thresholds cannot be described with only the mechanical cupula model. Considerable evidence suggests that vestibular thresholds arise in a more central region of the nervous system so that additional components are added to their behavior. While no current theoretical model can predict this more complex behavior of vestibular thresholds, it is well known that Zwislocki's theory of temporal summation can be applied to the threshold of audibility to explain its time variant behavior (Zwislocki, 1960).

"This prompted us to investigate whether the same theory could be applied to explain thresholds for detecting rotation around the yaw axis. Since Zwislocki's theory is based on the assumption of an exponential decay of neural excitation we used stimuli consisting of pairs of rectangular afferent pulses separated by time intervals of 150, 250, and 350 ms. The duration of one pulse was 250 ms. To obtain such afferent responses, the trajectories of the angular velocities had to be computed by solving the inverse differential equation of the combined cupula and chair mechanics and adding the result to a base velocity of 5 deg/s. The mechanical time constants used were 5 s and 5 ms for the cupula and 200 ms for the chair.

"Four subjects participated in the experiments. Each sat on a rotating chair in complete darkness. During each individual session the first of the two pulses remained unchanged at a subliminal amplitude. The thresholds for the second pulses were determined for the 3 discrete time intervals using an adaptive psychophysical procedure (Benson, 1989).

"If a time constant of temporal summation between 300 and 1000 ms is assumed, the threshold shift from the stimulus with 150 ms pulse interval to the stimulus with 350 ms pulse interval would be predicted to lie within the range of 2-4 dB. However, we measured a threshold shift of about 8 dB. This is much more than a model consisting of one temporal summing leaking integrator can explain.

"When we used a third order instead of a first order leaking integrator with a time constant of 190 ms +/- 20 ms, the model's predictions optimally fit our experimental data. This value was almost identical to the time constant of 200 ms measured in the auditory pathway. The vestibular pathway, however, seems to differ from the auditory pathway in the number of leaking integrators involved: it apparently contains three.

"By introducing such a third order lag with a transfer function of H(s) = (T(s+1)-3 in the vestibular system, it is possible to theoretically explain the modification of the Mulder product found empirically by Huang and Young (Huang & Young, 1981). The simulated predictions of our model for the relation between angular acceleration a and time to detect tmin are very similar to their results, which they estimated with the equation a x pow(tmin, 1.16) = 3.26."

Scott, W.B. (1999). Automatic GCAS: You can't fly any lower. *Aviation Week and Space Technology, 150*(5), 76-80.

Sekular, R., & Blake, R. (2002). *Perception* (4th ed.). NY: McGraw-Hill Higher Education.

Self, B.P., Breun, M., Feldt, B., Perry, C., & Ercoline, W.R. (2002). Assessment of pilot performance using a moving horizon (inside-out), a moving aircraft (outside-in), and an arc-segmented attitude reference display. Presented at the NATO symposium, *Spatial disorientation in military vehicles*. La Caruna, Spain: NATO Research & Technology Agency.

> The arc-segmented attitude display proved to be better than either the traditional moving horizon or the moving aircraft displays for unusual attitude recoveries by experienced and novice pilots.

Sipes, W.E., & Lessard, C.S. (1999). Spatial disorientation: A survey of incidence. In R.S. Jensen, B. Cox, J.D. Callister, & R. Lavis (Eds.), *Proceedings of the Tenth International Symposium on Aviation Psychology*. Columbus, OH: The Ohio State University.

Sklar, A., & Sarter, N. (1999). Good vibrations: Tactile feedback in support of attention allocation and human automation coordination. *Human Factors, 41*, 543-552.

Smith, D.R., Cacioppo, A.J., & Hinman, G.E., Jr. (1997). Aviation spatial orientation in relationship to head position, altitude interpretation, and control. *Aviation, Space, and Environmental Medicine, 68*(6), 472-8.

> "Recently, a visually driven neck reflex was identified as causing head tilt toward the horizon during VMC flight. If this is the case, then pilots orient about a fixed rather than moving horizon, implying current attitude instruments inaccurately present spatial information. The purpose of this study was to determine if the opto-kinetic cervical neck reflex has an effect dependent on passive (autopilot) or active control of the aircraft. Further, findings could help determine if the opto-kinetic cervical reflex is characteristic of other flight crewmembers.... There were 16 military pilots who flew two 13-min[ute] VMC low-level routes in a large dome flight simulator. Head position in relation to aircraft bank angle was recorded by a head tracker device. During one low-level route, the pilot had a supervisory role as the autopilot flew the aircraft (passive). The other route was flow manually by the pilot (active).... Pilots consistently tilted the head to maintain alignment with the horizon. Similar head tilt angles were found in both the active and passive flight phases. However, head tilt had a faster onset rate in the passive condition.... Results indicate the opto-kinetic cervical reflex affects pilots while actively flying or in a supervisory role as the autopilot flies. The consistent head tilt angles in both conditions should be considered in attitude indicator, HUD, and HMD designs. Further, results seem to indicate that non-pilot flight crewmembers are affected by the opto-kinetic cervical reflex which should be considered in spatial disorientation and airsickness discussions."

Snow, M.P., Reising, J.M., Liggett, K.K., & Barry, T.P. (1999). Flying complex approaches using a head-up display: Effects of visibility and display type. In *10th International Aviation Psychology Symposium*. Columbus, OH: Ohio State University.

Advanced head-up and head-down displays show a pathway-in-the sky and/or a synthetic terrain image for pilot orientation.

Solomonow, M., Lyman, J., & Freedy, A. (1977). Electrotactile two-point discrimination as a function of frequency, body site, laterality, and stimulation codes. *Annals of Biomedical Engineering, 5*, 47-60.

"The feasibility of frequency modulated two-point discrimination as a design concept for an electrocutaneous sensory substitution display has been studied. Three stimulation techniques were tested on human subjects: spatial stimulus, temporal stimulus, and frequency-on-frequency stimulus. The frequency-on-frequency technique yielded the lowest threshold when compared to the temporal and spatial techniques. In addition, some of the characteristic behavior of cutaneous sensation is discussed relating two-point discrimination with frequency, body sites, and stimulation codes. Implications of the results for clinical applications are reviewed."

Solomonow, M., Raplee, L., & Lyman, J. (1978). Electrotactile two-point discrimination as a function of frequency, pulse width and pulse time delay. *Annals of Biomedical Engineering, 6*, 117-125.

"The feasibility of frequency modulated two-point discrimination as a design concept for electrocutaneous sensory substitution displays has been investigated further. Two new parameters have been tested on human subjects for their effect on the two-point threshold: pulse width and pulse time delay (phase shift). The pulse width study has shown that 100-μsec pulses resulted in the lowest threshold for spatial stimulation while 10-μsec pulses yielded the lowest threshold for temporal stimulation. It was also shown that pulse phase shifts of 0 to 180° result in different threshold values. Phase shifts of 0 to 135° showed slight threshold improvement. The 180° phase shift yielded substantial improvement."

Spence, C. (2002). Multisensory attention and tactile information-processing. *Behavioral Brain Research, 135*, pp. 57-64.

Stapleford, R.L. (1968). Multimodality pilot model for visual and motion cues. *Proceedings of Fourth Annual NASA-University Conference on Manual Control* (NASA SP-192). Ann Arbor, MI: University of Michigan, 47-56.

Estimates of semicircular canal thresholds of detection for pitch, roll, and yaw accelerations, plus formulas for converting acceleration times into sensed velocities. The values given are 3.2 deg/sec for roll, 2.6 deg/sec for pitch, and 1.1 deg/sec for yaw. Also, utricle sensing of linear accelerations is discussed.

Stokes, A., Wickens, C.D., & Kite, K. (1990). *Display technology: Human factors concepts.* Warrendale, PA: SAE.

Taylor, J.B., & Kuchar, J.K. (2000). Helmet-mounted display symbology for terrain avoidance during low-level maneuvers. *International Journal of Aviation Psychology, 10,* 155-168.

Taylor, R.M., Bonner, M.C., Dickson, B., Howells, H., Miller, C.A., Milton, N., Pleydell-Pearce, K., Shadbolt, N., Tennison, J., & Whitecross, S. (2002). Cognitive cockpit engineering: Coupling functional state assessment, task knowledge management, and decision support for context-sensitive aiding. Chapter 8 in M.D. McNeese & M.A. Vidulich (eds.) *Cognitive systems engineering in military aviation environments: Avoid cogminutia fragmentosa!* Wright-Patterson AFB, OH: HSIAC, 253-314. Found at: http://iac.dtic.mil /hsiac/SOARs_TOCs.htm.

> "The UK Ministry of Defence (MOD) in conjunction with the Defence Evaluation Research Agency (DERA) have established a program of applied research concerned with the development of cockpit adaptive automation and decision aiding for military fast-jet pilots. The operational requirement for this *cognitive cockpit* project arises from the possibility of a highly automated future offensive air system, involving a mix of manned and uninhabited air vehicles. In complex, rapidly changing military environments, increased dependencies on automation present significant challenges to maintaining effective human cognitive involvement in systems functioning. A human-centered approach to system design is needed that is based on human cognitive requirements for the control of system functional purpose, decision-making usability, and effectiveness in context of use. Technology is needed to assist rather than replace the future aircrew in cognitive work with systems involving high levels of task automation. Support will be needed that is adaptive and context-sensitive, to be responsive to changing mission requirements, in particular for in-flight situation assessment and mission replanning, in other words, decision support to provide the right information, in the right way, and at the right time. Technology needs to consider the aircrew's physiological and behavioral state, adaptively responding to an individual's indications of overload, distraction, and incapacitation. This chapter describes a program of research in cognitive systems engineering that seeks to couple pilot functional state assessment, knowledge-based systems for situation assessment and decision support, with concepts and technologies for adaptive automation and cockpit adaptive interfaces. The intention is to provide a scientific quantitative assessment of a broad range of options for intelligent pilot-aiding. This is to be based on sound cognitive systems engineering principles for system cognitive control, which keeps the pilot in control of the system, rather than the system controlling the pilot."

Tokumaru, O., Kaida, K., Ashida, H., Mizumoto, C., & Tatsuno, J. (1998). Visual influence on the magnitude of somatogravic illusion evoked on advanced spatial disorientation demonstrator. *Aviation, Space, and Environmental Medicine, 69*(2), 111-6.

The somatogravic illusion (SGI) is a kind of spatial disorientation caused by a linear sustained acceleration. Pilots believe that visual cues, such as a visible horizon or texture flow, reduce this illusion. This study was performed to evaluate the influence of visual stimuli on the SGI using the Advanced Spatial Disorientation Demonstrator (ASDD). There were eight healthy males who were exposed to a 0.58 g x axis linear acceleration on the ASDD, where the direction of the resultant gravito-inertial force was equivalent to 30 degrees pitch-up. One of the following visual stimuli was presented during each acceleration: BLANK (no visual cues); HORIZON (a visible horizon without motion); and TEXTURE (vertical lines moving toward the subject evoking vection). The subjective magnitude of the SGI in ordinal scale was observed; and in interval scale, the deviation of the moving point kept at the subjective horizon was observed. The differences among visual stimuli were analyzed. The subjective magnitude of the SGI ($p < 0.01$) and the deviation of the moving point ($p < 0.05$) were significantly smaller in HORIZON than in BLANK and TEXTURE. No difference was demonstrated between BLANK and TEXTURE. The linear vection produced by the TEXTURE stimulus did not affect the SGI. The data indicated that the presence of a visible horizon reduced the magnitude of the SGI. On the other hand, the presence of a vection stimulus did not influence the magnitude of the SGI.

Tokumaru, O., Kaida, K., Ashida, H., Yoneda, I., & Tatsuno, J. (1999). EEG topographical analysis of spatial disorientation. *Aviation, Space, and Environmental Medicine, 70*(3), 256-263.

Impact of vection and the somatographic illusion on EEG frequency topography were evaluated. Characteristic EEG patterns were found for both conditions of spatial disorientation.

Ungerleider, L.G., & Haxby, J.V. (1994). What and where in the human brain. *Current Opinions in Neurobiology, 4*, 157-165.

United States Army (2000). Aeromedical Training for Flight Personnel (FM #3-04.301), Chapter 9. Washington, D.C.: Headquarters, Department of the Army.

United States Navy (1991). *United States Naval Flight Surgeon's Manual* (3rd ed.). Pertinent section obtained from: www.vnh.org/FSManual/03/03SpatialDisorientation.html.

van Erp, J.B.F., Veltman, H.J.A., & van Veen, H.A.H.C. (2003). A tactile cockpit instrument to support altitude control. *Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: HFES, 114-118.

Veronneau, S.J.H. (2000). *Civilian spatial disorientation mishap experience*. San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Mishap%20Studies/Veronnenau.pdf

Presents NTSB and FAA statistics for civilian SD mishaps from 1982-1993. Accidents typically involve non-instrument-rated pilots attempting to complete VFR flights in IMC.

Vinje, E.W., & Pitkin, E.T. (1972). Human operator dynamics for aural compensatory tracking. *IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-2*(4), 504-512.

> Aural, visual, and combined displays for a tracking task showed improved performance with the combined format.

Wandell, B.A. (1999). Computational neuroimaging of human visual cortex. *Annual Review of Neuroscience, 22*, 145-173.

Warren, R., & Wertheim, A.H. (Eds.) (1990). *Perception and control of self-motion*. Hilldale, NJ: Erlbaum.

Weinstein, L., & Wickens, C.D. (1992). Use of nontraditional flight displays for the reduction of central visual overload in the cockpit. *International Journal of Aviation Psychology, 2*(2), 121-142.

Welch, R.B., & Warren, D.H. (1986). Intersensory interactions. In K.R. Boff, L. Kaufman, & J.P. Thomas (Eds.), *Handbook of Perception and Human Performance* (Volume I), pp.25.1-25.36. New York: John Wiley & Sons.

> "...[T]he procedure of examining each of the senses as if it were independent of the others can lead, at best, to only partial understanding of everyday perceptual experience." "...[F]or human beings vision is more precise and accurate than any other modality for the perception of spatial events, whereas audition is best suited for the perception of temporal events." "The preponderance of evidence indicates that when the accessory stimulus is of low-to-moderate intensity the effect on the primary stimulus is one of facilitation, whereas highly intense accessory stimuli are inhibitory." Another important variable is the timing and duration of each stimulus. Spatial events and "the[ir] order of decreasing relative acuity...[are] vision, touch/kinesthesis, and audition." Touch and pressure have strong effect on orientation. "...[T]he perception of visual direction requires the presence of information regarding felt ocular and head position and that if this information is incorrect, the perception is also incorrect." "According to the directed-attention hypothesis, the degree to which two sensory modalities bias one another is determined by the observer's distribution of attention to each of them. Thus if a great deal of attention is paid to one modality relative to the other, the former will strongly bias the latter but will not be biased very much itself."

Wenzel, E.M. (1993). Localization in virtual acoustic displays. *Presence, 1*(1), 80-107.

> "This paper discusses the development of a particular spatial display medium, the virtual acoustic display. Although the technology can stand alone, it is envisioned ultimately to be a component of a larger multisensory environment and will no doubt find its greatest utility in that context. A general philosophy of the project has been that the development of advanced computer interfaces should be driven first by an understanding of human perceptual requirements, and secondarily by technological capabilities or constraints. In expanding on this view, the paper addresses why virtual acoustic displays are useful,

characterizes the abilities of such displays, reviews some recent approaches into their implementation and application, describes the research project at NASA Ames in some detail, and finally outlines some critical research issues for the future."

Wickens, C.D. (1984). Processing resources in attention. In R. Parasuraman & D.R. Davies (Eds.) *Varieties of attention*. New York: Academic Press, 63-258.

Wickens' seminal work on Multiple Resource Theory (MRT).

Wickens, C.D. (1986). The effects of control dynamics on performance. In K.R. Boff, L. Kaufman, & J.P. Thomas (Eds.), *Handbook of Perception and Human Performance (Volume II)*, pages 39.1-39.60. New York: John Wiley & Sons.

Motion effects on the vestibular system, display guidance, and auditory redundancy to visual displays. A table summarizes the roles of the utricle and semicircular canals in various flight situations, and the resulting illusions. Vision fixation is also discussed: "the dwell of 400-600 msec is the minimum time necessary to acquire foveal information appropriate for control action." "...[V]ery rapid dwells of 125-200 msec...appear to be 'global checks' to affirm that the indicator is in the right general location, rather than dwells defined to extract quantitative information." Wickens later asserts that integrated displays are naturally the best for scanning and control, and that "a single error indicator [that] can make excursions in more than one orthogonal axis should be of considerable benefit to tracking performance." This rationale supports our SD icon design (Figure 7). Later in the chapter, in a section on auditory displays, Wickens states, "...auditory displays of the analog information used in tracking can never be expected to replace visual displays. However, their value as a redundant source of information can be realized in situations when visual work load is already high."

Wickens, C.D. (1995). Designing for stress. In J. Driskell & E. Salas (Eds.), *Stress and Human Performance*. Mahwah, NJ: Erlbaum.

Wickens, C.D. (2002). Situation awareness and workload in aviation. *Current Directions in Psychological Science, 11*(4), 128-133.

"Designers need to understand these three general issues [frame of reference, degree of integration, prediction] and integrate the principles of visual attention, spatial cognition, and manual control to craft the configuration of aircraft displays that will support all of the needed tasks, without overloading attentional capabilities." Auditory tasks tend to be more interrupting and less interruptible than tasks even with a higher priority. "...[E]ffective models of mental workload should be able to predict the circumstances in which the workload of routine performance is raised to such a level that resources are not available to maintain situation awareness..."

Wickens, C.D. (2003). Aviation displays. In P. Tsang & M. Vidulich (Eds.), *Principles and practices of aviation psychology*. Mahwah, NJ: Lawrence Erlbaum, 147-199.

Wickens, C.D., & Hollands, J.G. (2000). *Engineering Psychology and Human Performance.* Upper Saddle River NJ: Prentice Hall.

Wickens, C.D., & Rose, P.N. (2001). *Human factors handbook for displays: Summary of findings from Army Research Lab's advanced displays and interactive displays federated laboratory.* Thousand Oaks, CA: Rockwell Sciences.

> "This handbook addresses many relevant issues for enhancing human information processing. Guiding attention with cueing, highlighting, and alarms or alerts have proven value. Flashing is especially compelling. Target tunneling is one potential down-side to focusing attention on one item to the exclusion of others. Information rich displays have clutter issues, which can be alleviated by filtering and decluttering, both of which have drawbacks, namely determining a priori what is or is not essential information. Color coding is useful; intensity coding is generally less useful. Spatial separation techniques seem promising, but additional research is needed. Choosing the type of display (head-mounted, see-through, or traditional CRT or LCD), and the frame of reference are important considerations in design, especially for orientation and navigation tasks. Enhancing situation awareness is a goal of display design; information integration aids achieving and maintaining SA. Automated enhancement of information, based upon the user's inferred intent, is one solution to the information overload problem."

Wickens, C.D., Sandry, D., & Vidulich, M.I. (1983). Compatibility and resource competition between modalities of input, central processing, and output: Testing a model of complex task performance. *Human Factors, 25*, 227-228.

Wickens, C.D., Vincow, M., & Yeh, M. (2003). Design applications of visual spatial thinking: The importance of frame of reference. In P. Shah and A. Miyaki (Eds.), *Handbook of Visual-spatial thinking.* Cambridge, UK: Cambridge University Press.

Worringham, C.J., & Beringer, D.B. (1989). Operator orientation and compatibility in visual-motor task performance. *Ergonomics, 32*, 387-399.

Zwislocki, J. (1960). Theory of temporal auditory summation. *Journal of the Acoustic Society of America, 32*, 1046-1060.

X. Acronyms & Terms

3D	three-dimensional
A	attitude
AFB	air force base
AFRL	Air Force Research Laboratory
AFSA	Air Force Safety Agency
AFSC	Air Force Safety Center
AGL	(altitude) above ground level
AI	attitude indicator
Alt	altitude
ANOVA	analysis of variance
AOA	angle of attack
Ap	perceived attitude
ASDD	advanced spatial disorientation demonstrator
At	true attitude
attn	attention
B	bank
Baro, baro	barometric (altitude)
Bp	perceived bank
C#	a computer language (pronounced “see sharp”)
C-17	4-engine USAF cargo aircraft
CF	Canadian forces
CF-18	Canadian fighter attack jet
CFIT	controlled flight into terrain
Class A	mishap that costs > $1M, or has loss of life, or causes permanent total disability, or destroys an aircraft
Class B	mishap that costs > $200K and < $1M, or permanent partial disability, or hospitalization of 3 or more people
Class C	mishap that costs > $20K and < $200K, or injury that results in lost work after the day or shift it occurred, or disability (source: http://www2.faa.gov/arp/environmental/5054a/MOAFINALVERSION.doc)
CRE	control reversal error(s)
CRT	cathode ray tube
DA	difference in attitude: |**Ap-At**|
deg	degree(s)
DERA	Defence Evaluation Research Agency (UK)
EEG	electroencephalogram
F-15	USAF two-seat high performance fighter attack jet
F-22	USAF’s newest stealthy fighter attack jet
FAA	Federal Aviation Administration
FDM	flight data monitoring (European term for FOQA)
FMA	follow-me aircraft
fMRI	functional magnetic resonance imaging
FOQA	flight operations quality assurance (routine data collection and analyses)
FOR	frame of reference
FOV	field of view

FY	fiscal year
G	acceleration due to gravity
GAIN	global aviation information network
GCAS	ground collision avoidance system
GD	grapefruit display
G-LOC	G-induced loss of consciousness
HDD	head-down display
hdg	heading
HECI	Crew Systems Development Branch (part of HEC, the Crew System Interface Division, which is part of the Human Effectiveness Directorate, HE)
HITL	human in the loop
HITS	highway in the sky
HMD	helmet-mounted display
HUD	head-up display
Hz	Hertz (cycles per second; so, 2 Hz is 2 cycles per second)
IAS	indicated airspeed
IFR	instrument flight rules
ICAO	International Civil Aviation Organization
IMC	instrument meteorological conditions (poor visibility)
IRB	institutional review board
ISD	incapacitating SD
LSA	loss of SA
Lt	lieutenant
MA&D	Micro Analysis & Design
MAAD	Micro Analysis & Design
mag	magnetic
Micro Saint	MA&D's discrete event simulation tool
MFOQA	military FOQA (the military's FOQA program)
MOD	Ministry of Defence (UK)
MRT	(Wickens') multiple resource theory
msl	(altitude above) mean sea level
NTSB	National Transportation Safety Board
NVG	night vision goggles
OKCR	opto-kinetic cervical reflex
P	pitch
PET	positron emission tomography
PI	principal investigator
PITL	pilot in the loop
Pp	perceived pitch
RAlt	radio or radar altitude (height above the ground)
rCBF	regional cerebral blood flow
RSD	recognized SD
SA	situation awareness
SAVVOY	somatic, auditory, visual, vestibular, olfactory, psychomotor and cognitive workload scores
SBIR	Small Business Innovation Research

SD	spatial disorientation
sec	second(s)
SGI	somatogravic illusion
SO	spatial orientation
SVS	synthetic vision system
SXGA	super extended graphics array
TCAS	traffic alert and collision avoidance system
TLS	tactor locator system
TSAS	tactile situational awareness system
Type 1 SD	unrecognized SD
Type 2 SD	recognized SD
Type 3 SD	incapacitating SD
UAV	uninhabited air vehicle
UH-60	US Army's frontline utility helicopter
UK	United Kingdom (England)
US, U.S.	United States
USAF	United States Air Force
USD	unrecognized SD
V-22	tilt rotor, vertical/short takeoff and landing, multi-mission aircraft used primarily by the US Navy, Marine Corps, and Air Force
VACP	visual, auditory, cognitive, psychomotor – resource components which comprise Wickens' multiple resource theory
VAP	variance of perceived attitude
Var	variance
VFR	visual flight rules
VMC	visual meteorological conditions (good visibility)
VOR	vestibulo-ocular reflex
VSI	vertical speed indicated